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CONCEPTS. VOLUME 1: DEFINITION OF THERMAL  
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### DEVELOPMENT OF THERMAL STRATIFICATION AND DESTRATIFICATION SCALING CONCEPTS - VOLUME I Definition of Thermal Stratification Scaling Parameters and Experimental Investigations

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## FOREWORD

This document is Volume I of the final report of NASA Contract NAS8-24747, "Development of Thermal Stratification and Destratification Scaling Concepts." Mr. L. A. Holmes served as the program manager for the initial phase of this study. In August 1970 Mr. T. M. Lovrich assumed the responsibilities of program manager and is responsible for the performance of this study. The study was conducted for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration under the technical direction of Mr. T. W. Winstead, Thermodynamics and Fluid Mechanics Branch, Propulsion Division, Propulsion and Vehicle Engineering Laboratory.

Appreciation is expressed to Dr. S. H. Schwartz, Associate Professor Mechanical Engineering, West Virginia University for his assistance as a consultant. The authors wish to recognize Mr. L. A. Holmes, Engineering Instructor, Modesto Jr. College in California, for initiating most of the initial scaling concepts analytical work and test design, and to Mr. T. W. Winstead, MSFC/NASA Contract Technical Supervisor, for his assistance during the performance of this research study; and to J. E. Rogan, Heat and Mass Transfer Branch Chief, of MDAC for his support in the performance of this research study.

The final report consists of two volumes:

- Volume I     Definition of Thermal Stratification Scaling  
                 Parameters and Experimental Investigation
- Volume II    Stratification — Experimental Data

Volume I is a report of the final results, conclusions, and recommendations of the study. It includes a presentation of the analytical methods used in defining the thermal stratification dimensionless

scaling parameters and the experimental investigation performed with saturated Freon 113 in three closed tanks thermodynamically and geometrically scaled for determining the validity of these scaling parameters. Volume II contains a presentation of the experimental data collected and utilized in this stratification research study.

Work performed with the 6 inch and 18 inch diameter tanks was supported under this contract, while the work performed with the 12 inch diameter tank was primarily supported by MDAC-West IRAD "Low-G Fluid Mechanics and Heat Transfer" funding.

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## ABSTRACT

A detailed study to determine the important dimensionless parameters associated with the thermal stratification and pressure history of a heated container of liquid and its vapor was made. A test program was then designed to verify the validity of these scaling parameters. The Modified Grashof number, the Fourier number, and an Interface number were the three pi-groups that were parameterized using a single test liquid, Freon 113. Three cylindrical test tanks with spherical dome end caps, 6, 12, and 18 inches in diameter with an L/D of 3, were built. Blanket heaters covered the tanks and 77 thermocouples monitored the temperatures of the liquid, the ullage, the tank walls, and the foam insulation encapsulating the tank. A centrifuge was used for the 6 inch tank to preserve the same scaling parameter values between it and the larger tanks. Tests were conducted over a range of  $Gr^*$  values, between  $10^{14}$  to  $10^{16}$ , and the degree of scaling was checked by comparing the dimensionless pressures and temperatures for each scaled pair of tests. Results indicate that the bulk liquid temperature, the surface temperature of the liquid, and the tank pressure can be scaled with the three dimensionless parameters. Some deviation was, however, found in the detailed temperature profiles between the scaled pairs of tests.

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## NOMENCLATURE

$c_p$	specific heat at constant pressure
$c_v$	specific heat at constant volume
$d$	nozzle diameter
$D$	tank diameter
$ Fo$	Fourier number, $\nu \theta / D^2$
$g$	gravitational constant
$Gr^*$	Modified Grashof number, $g \beta q'' L^4 / k \nu^2$
$Gr_H^*$	Modified Grashof number based on $q_H''$
$Gr_\ell^*$	Modified Grashof number based on $q_\ell''$
$h_{fg}$	latent heat of vaporization
$I$	Interface number $q'' D C_p / h_{fg} k_\ell$
$k$	thermal conductivity
$L$	liquid height
$m$	mass
$Ma^*$	Marangoni number $(q'' D^2 / k_\ell \nu_\ell \alpha_\ell) \frac{d\sigma}{dT}$
$p$	pressure
$Pr$	Prandtl number, $\mu C_p / k$
$q''$	heat flux
$q_H''$	heat flux at heater blanket
$q_\ell''$	heat flux to liquid
$Ra^*$	Modified Rayleigh number, $(Gr^* \cdot Pr)$

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$Re_j$	jet Reynolds number, $U_j d / \nu_\ell$
$t$	time
$T$	temperature
$u$	velocity in x direction
$v$	velocity in y direction
$x$	spatial coordinate
$y$	spatial coordinate
$Y$	tank height

#### Greek Symbols

$\alpha$	thermal diffusivity, $k / \rho c_p$
$\beta$	coefficient of thermal expansion
$\theta$	stratification test period
$\mu$	viscosity
$\nu$	kinematic viscosity, $\mu / \rho$
$\rho$	density
$\sigma$	surface tension
$\tau$	dimensionless time, $t / \theta$
$\omega$	acceleration due to rotation

#### Subscripts

A, B	refers to different scaled tanks
b	bulk
f	final
h	hydrostatic
i	initial
j	jet
$\ell$	liquid

m	motion
M	mixing
r	reference
s	storage
u	ullage
v	vapor
1, 2	refers to two identical tests with same tank



## Section I

### INTRODUCTION

Many future space missions will rely on long-term cryogenic-chemical propellant storage and fuel-transfer systems. The feasibility of these mission concepts and design configurations will continue to be strongly influenced by the ability to effectively design a cryogenic propellant storage system. Consequently, it is important that the designer have a strong technical platform from which to predict tank design pressures and thermodynamic and fluid mechanical behavior in a low-g, near-zero gravity environment.

Although considerable ground-test data have been gathered, and numerous analyses carried out in the area of propellant thermal stratification (and destratification), the basic scaling parameters that provide the relationship between the ground model tests and the full-scale flight vehicle have not been adequately substantiated. The associated phenomena are sufficiently complicated so that useful scaling parameters cannot be established by analytical means alone. Thus, a systematic analytical and experimental study of scaling parameters for thermal stratification (and destratification) was made in this program. It was the purpose of this program to substantiate the validity of the defined scaling groups.

The conservation equations describing the liquid and its vapor phase were nondimensionalized and the resulting dimensionless parameters were used to define a test matrix. The test program was designed to determine whether or not the dimensionless pressures and temperatures met the scaling criteria for two tanks which have dimensionless parameters equal to one another. Three geometrically and thermodynamically scaled test tanks were designed and fabricated. A destratification jet orifice was at the bottom of each tank. These tanks were capable of heating the liquid and its vapor, either separately or together at various liquid levels. Seventy-seven thermocouples were

installed in the liquid, the vapor, the tank walls, and the insulation. Temperature and pressure measurements were monitored to verify the scaling parameters.

Difficulties were encountered in obtaining scalable stratification/destratification data. These were in the areas of tank material incompatibilities with Freon 113 and the high-g effects on the instrumentation equipment during testing on the centrifuge. Consequently, a new test matrix was defined and the data retrieving system was revised midway into the program. The number of basic scaling tests was reduced and a single fluid, Freon 113, was used.

The new test plan consisted of 20 scaling tests and an additional 17 tests for determining data reproducibility. The program tasks were to: (1) define the scaling parameters analytically, (2) fabricate the test apparatus, (3) define a test program, (4) conduct tests, and (5) reduce and analyze temperature and pressure data based upon the defined scaling groups.

During the tests, the three scaling pi groups,  $Fr$ ,  $Gr^*$ , and  $I$  were maintained constant according to the test matrix. These tests covered a range of Modified Grashof numbers, from  $10^{14}$  to  $10^{16}$ , Fourier numbers, from  $10^{-6}$  to  $10^{-4}$ , and Interface numbers, from  $7.54 \times 10^{-3}$  to  $2.42 \times 10^{-1}$ . Destratification tests were conducted at the termination of each stratification test by activating a pump which produced an axial mixing jet. The jet Reynolds numbers ranged from 20,000 to 45,100.

This document discusses the analytical procedures, the experimental equipment, the test matrix and experimental program definition, testing, the results, and the conclusions and recommendations.

## Section 2

### DIMENSIONLESS PARAMETERS

#### 2.1 INTRODUCTION

This phase of the study was directed towards identification of the dimensionless parameters associated with the thermal stratification process. The technique of nondimensionalizing the set of conservation equations and boundary conditions which describe the heated liquid-vapor system was used to determine the parameters analytically. This method was selected because it lent itself readily to the stratification process and is a rigorous and accurate technique. However, it should be noted that the set of dimensionless parameters obtained can only be as accurate as the equations which describe the physical process. Furthermore, it has been assumed that a unique solution to this set of equations exists.

The first step in the nondimensionalization process was to write the conservation equations and the boundary conditions describing a specific tank geometry and liquid-vapor system. For simplification, the thermodynamic system was limited to a flat liquid-vapor interface and only a 2-phase system was considered. The conservation equations were written separately for the liquid and the vapor. The boundary conditions include both the tank walls and the liquid-vapor interface separating the two phases.

The next step in the nondimensionalization process was to select a set of quantities, characteristics of the physical system, which include all of the basic physical units of the system. These characteristic values, such as length and time, were then used to nondimensionalize the independent and dependent variables included in the governing equations and the boundary conditions. Selecting the proper characteristic quantities is necessary to provide a consistent and useful set of scaling parameters. These values are measurable constants that are characteristic, yet distinguishable, and can be related to a specific tank.

The resulting dimensionless variables are then substituted back into the differential equations thus transforming them into a set of dimensionless differential equations and boundary conditions. The dimensionless coefficients associated with these equations are the dimensionless parameters. The following discussion will cover in detail the steps required to obtain these parameters.

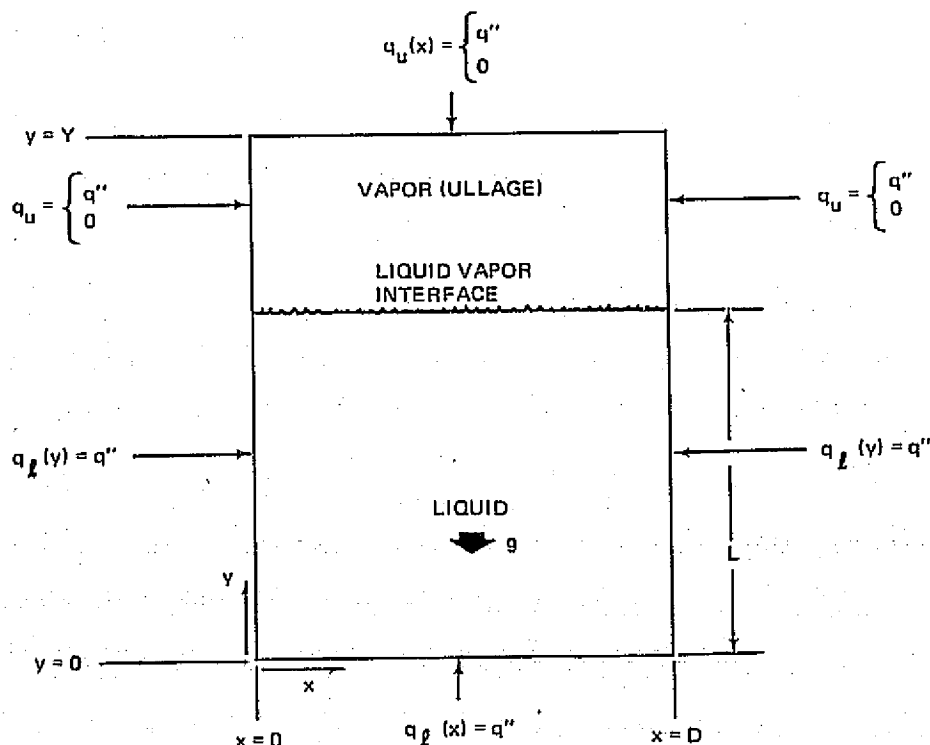
## 2.2 CONSERVATION EQUATIONS AND BOUNDARY CONDITIONS

A two-dimensional system in cartesian coordinates was used when developing the set of conservation equations and boundary conditions for the thermal stratification process. However the same group of dimensionless parameters would be achieved without this simplification. Figure 2-1 illustrates the overall two-dimensional system and the boundaries. The governing equations were written in differential form for an arbitrary location both in the liquid and the vapor where the gravity vector is in the y direction. It was assumed that the transport properties are constant and that liquid is incompressible.

The following set of equations apply to a single component, two-phase system with a flat liquid-vapor interface. Holmes (Ref 1) presented a more general

CR 108-1

FIGURE 2-1  
GENERALIZED STORAGE SYSTEM



set of equations to allow for a curved interface, two components, and 3 phases. The momentum equations listed below incorporate the Boussinesq approximation which gives rise to the  $g\beta\Delta T$  term. In addition, components of the total pressure are listed separately. The pressure  $p$  at a point is expressed as

$$p = p_{\text{ref}} + p_h + p_m \quad (2-1)$$

where  $p_{\text{ref}}$  is the pressure at the location where  $p_h$ , the hydrostatic pressure, is zero. The value of  $p_m$  is that pressure due to motion and is the dynamic pressure. Thus, in the liquid  $p_{\text{ref}} = p_{\text{v surface}}$  whereas in the vapor  $p_{\text{ref}} = p_{\text{v y=Y}}$  (i.e., this is effectively the measured ullage pressure). The  $g\beta\Delta T$  term in the momentum equations comes from the  $\partial p_h / \partial x$  term and the body force term and only the  $\partial p_m / \partial x$  term remains. The pressure of the ullage,  $p_v$ , is found in the vapor-energy equation and is defined by the equation of state. The measured value of  $p_v$  will be close to the total pressure,  $p$ , since  $p_m$  is small under the conditions of this study. Thus, the values of  $p_m$  and  $p_v$  are entirely sufficient.

#### LIQUID REGION:

##### Conversion of Mass:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (2-2)$$

##### Conservation of Momentum:

$$\frac{Du}{Dt} = \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = - \frac{1}{\rho_\ell} \frac{\partial p_m}{\partial x} + \nu_\ell \nabla^2 u \quad (2-3)$$

$$\frac{Dv}{Dt} = \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = - \frac{1}{\rho_\ell} \frac{\partial p_m}{\partial y} + \nu_\ell \nabla^2 v + g \beta_\ell \Delta T \quad (2-4)$$

##### Conservation of Energy:

$$\frac{DT}{Dt} = \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha_\ell \nabla^2 T + \frac{2\nu_\ell}{c_p} \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 \right] \quad (2-5)$$

## VAPOR REGION:

### Conservation of Mass:

$$\frac{\partial \rho_v}{\partial t} + \frac{\partial \rho_v u}{\partial x} + \frac{\partial \rho_v v}{\partial y} = 0 \quad (2-6)$$

### Conservation of Momentum:

$$\frac{Du}{Dt} = \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = - \frac{1}{\rho_v} \frac{\partial p_m}{\partial x} + \nu_v \nabla^2 u \quad (2-7)$$

$$\frac{Dv}{Dt} = \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = - \frac{1}{\rho_v} \frac{\partial p_m}{\partial y} + \nu_v \nabla^2 v + g \beta_v \Delta T \quad (2-8)$$

### Conservation of Energy:

$$\begin{aligned} \frac{DT}{Dt} = \frac{1}{c_v} \frac{D(p_v/\rho_v)}{Dt} + \frac{1}{\rho_v c_v} \frac{Dp_v}{Dt} + \frac{\nabla \cdot k \nabla T}{\rho_v c_v} \\ + \frac{\mu_v}{\rho_v c_v} \left[ 2 \left\{ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 \right\} + \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2 - \frac{2}{3} \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)^2 \right] \end{aligned} \quad (2-9)$$

### Equation of State:

$$p_v = f(\rho_v, T_v) \quad (2-10)$$

## LIQUID-VAPOR INTERFACE BOUNDARY CONDITIONS:

### Velocity:

#### Continuous Tangential Velocity:

$$u_\ell = u_v \quad (2-11)$$

Normal Velocity:

$$v_{\text{surface}} = v_l, v_v = v_{\text{surface}} + \frac{dy}{dt} \left( \frac{\rho_l - \rho_v}{\rho_v} \right) \quad (2-12)$$

Temperature:

$$T_v = T_l \quad (2-13)$$

Energy:

$$k_l \left. \frac{\partial T}{\partial y} \right|_l - k_v \left. \frac{\partial T}{\partial y} \right|_v = \rho_l h_{fg} \frac{dy}{dt} \quad (2-14)$$

Shear:

$$\rho_l \nu_l \left. \frac{\partial u}{\partial x} \right|_l - \rho_v \nu_v \left. \frac{\partial u}{\partial x} \right|_v = \frac{d\sigma}{dT} \frac{dT}{dx} \quad (2-15)$$

EXTERNAL BOUNDARY CONDITIONS:

Velocity:

$$u(0, y, t) = v(0, y, t) = 0 \quad ; \quad 0 \leq y \leq Y \quad (2-16)$$

$$u(D, y, t) = v(D, y, t) = 0 \quad ; \quad 0 \leq y \leq Y \quad (2-17)$$

$$u(x, 0, t) = v(x, 0, t) = 0 \quad ; \quad 0 \leq x \leq D \quad (2-18)$$

$$u(x, Y, t) = v(x, Y, t) = 0 \quad ; \quad 0 \leq x \leq D \quad (2-19)$$

Temperature:

$$k_l \left. \frac{\partial T}{\partial x} \right|_l (0, y, t) = -q'' \quad ; \quad 0 \leq y \leq L \quad (2-20)$$

$$k_v \left. \frac{\partial T}{\partial x} \right|_v (0, y, t) = \begin{cases} -q'' \\ 0 \text{ (no ullage heating)} \end{cases} \quad ; \quad L < y \leq Y \quad (2-21)$$

$$k_{\ell} \frac{\partial T}{\partial x} (D, y, t) = q'' \quad ; \quad 0 \leq y \leq L \quad (2-22)$$

$$k_v \frac{\partial T}{\partial x} (D, y, t) = \begin{cases} q'' \\ 0 \end{cases} \quad ; \quad L < y \leq Y \quad (2-23)$$

$$k_{\ell} \frac{\partial T}{\partial y} (x, 0, t) = -q'' \quad ; \quad 0 \leq x \leq D \quad (2-24)$$

$$k_v \frac{\partial T}{\partial y} (x, Y, t) = \begin{cases} q'' \\ 0 \end{cases} \quad ; \quad 0 \leq x \leq D \quad (2-25)$$

### INITIAL CONDITIONS:

$$T(x, y, 0) = T_i(x, y) \quad (2-26)$$

$$u(x, y, 0) = 0 \quad (2-27)$$

$$v(x, y, 0) = 0 \quad (2-28)$$

$$\rho(x, y, 0) = \rho_i(x, y, 0) \quad (2-29)$$

### 2.3 CHARACTERISTIC VALUES

The characteristic quantities were chosen for the length, mass, temperature, and time system and are:

- $D$  - Characteristic Length (ft)
- $\rho_{\ell} D^3$  - Characteristic Mass (lbm)
- $\theta$  - Characteristic Time (sec)
- $q'' D / k_{\ell}$  - Characteristic Temperature ( $^{\circ}R$ )
- $q'' \theta / D$  - Characteristic Pressure ( $p_v$ ) ( $lb_f / ft^2$ )
- $\rho_{\ell} D^2 / \theta^2$  - Characteristic Dynamic Pressure ( $p_m$ ) ( $lb_f / ft^2$ )

where

- $D$  is the tank diameter,
- $\rho_{\ell}$  is the density of the liquid phase,
- $q''$  is the wall heat flux, and
- $k_{\ell}$  is the thermal conductivity of the liquid phase.



The use of the tank diameter as a characteristic length and the liquid density to define the characteristic mass is a commonly accepted practice in modeling. The selection of  $\theta$  as the characteristic time is generally more convenient than  $\sqrt{D/g}$ . Here  $\theta$  could be considered to be the mission time or the stratification experiment time. The wall heat flux,  $q''$ , multiplied by the ratio  $D/k_f$ , used to define the characteristic temperature, is also a value accurately established prior to most vehicle flights or experiments. The measured constant heater input heat flux,  $q''$ , is used for determining the characteristic pressure and temperature values.

#### 2.4 NONDIMENSIONALIZATION OF EQUATIONS

The characteristic quantities are used to obtain the transformation of the differential equations from a dimensional to a dimensionless form. All variables can be nondimensionalized directly from these quantities except for pressure where the terms  $p_m$  and  $p_v$  must be treated separately. The value of  $p_m$  is determined by fluid motion and should be nondimensionalized with a form such as  $\rho V^2$ . Hence, the value  $\rho_l D^2/\theta^2$  will be used. On the other hand  $p_v$  is essentially the measured tank pressure and is related to  $T$  through the equation of state. Thus, the selection of a characteristic value to nondimensionalize  $p_v$  can be obtained from the equation of state. It is convenient to use the perfect gas law

$$p_v = \rho_v R T_v \quad (2-30)$$

which does not result in a loss of generality. Thus, nondimensionalizing the right-hand side of the equation with the characteristic temperature yields:

$$p_v = \left( \frac{q''\theta}{D} \right) \left[ \frac{Pr}{Fo} \frac{R}{c_p} \right] \bar{\rho}_v \bar{T}_v \quad (2-31)$$

which indicates that the dimensional form  $(q''\theta/D)$  can be used as a characteristic pressure, hence

$$\bar{p}_v = \frac{p_v}{(q''\theta/D)} \quad (2-32)$$

The form  $(q''\theta/D)$  can also be obtained through a physical argument where  $P_{\text{final}} \sim (Q_{\text{TOT}}/m) \sim (q''\theta/D)$ . The resulting dimensional variables will be used

$$\bar{x} = \frac{x}{D}, \quad \bar{y} = \frac{y}{D} \quad (2-33)$$

$$\bar{u} = \frac{u}{D/\theta}, \quad \bar{v} = \frac{v}{D/\theta} \quad (2-34)$$

$$\bar{p}_m = \frac{p_m}{\rho_\ell D^2/\theta^2}; \quad \bar{p}_v = \frac{p_v}{q''\theta/D} \quad (2-35)$$

$$\tau = \frac{t}{\theta}, \quad \bar{\Delta T} = \frac{\Delta T}{q''D/k_\ell} \quad (2-36)$$

where

$\theta$  = Time (duration of stratification test)

#### NORMALIZED DIFFERENTIAL EQUATIONS:

Liquid Region:

Conservation of Mass:

$$\frac{\partial \bar{u}}{\partial \bar{x}} + \frac{\partial \bar{v}}{\partial \bar{y}} = 0 \quad (2-37)$$

Conservation of Momentum:

X component:

$$\frac{D\bar{u}}{D\tau} = \frac{\partial \bar{u}}{\partial \tau} + \bar{u} \frac{\partial \bar{u}}{\partial \bar{x}} + \bar{v} \frac{\partial \bar{u}}{\partial \bar{y}} = - \frac{\partial \bar{p}_m}{\partial \bar{x}} + \frac{\nu_\ell \theta}{D^2} \nabla^2 \bar{u} \quad (2-38)$$

or

$$\frac{D\bar{u}}{D\tau} = - \frac{\partial \bar{p}_m}{\partial \bar{x}} + Fo \cdot \nabla^2 \bar{u} \quad (2-39)$$

where

$$Fo = \frac{\nu_\ell \theta}{D^2} \quad (2-40)$$

Y component:

$$\frac{D\bar{v}}{D\tau} = \frac{\partial \bar{v}}{\partial \tau} + \bar{u} \frac{\partial \bar{v}}{\partial \bar{x}} + \bar{v} \frac{\partial \bar{v}}{\partial \bar{y}} = - \frac{\partial \bar{p}_m}{\partial \bar{y}} + \frac{\nu_\ell \theta}{D^2} \nabla^2 \bar{v} + \frac{g \beta_\ell \theta^2 q''}{k_\ell} \Delta \bar{T} \quad (2-41)$$

or

$$\frac{D\bar{v}}{D\tau} = - \frac{\partial \bar{p}_m}{\partial \bar{y}} + Fo \cdot \nabla^2 \bar{v} + Gr^* \cdot Fo^2 \cdot \Delta \bar{T} \quad (2-42)$$

where

$$Gr^* = \frac{g \beta_\ell q'' L^4}{\nu_\ell^2 k_\ell} \quad (2-43)$$

Conservation of Energy:

$$\frac{D\bar{T}}{D\tau} = \frac{\partial \bar{T}}{\partial \tau} + \bar{u} \frac{\partial \bar{T}}{\partial \bar{x}} + \bar{v} \frac{\partial \bar{T}}{\partial \bar{y}} = \frac{\alpha_\ell \theta}{D^2} \nabla^2 \bar{T} + \frac{k_\ell \nu_\ell}{q'' D c_{p\theta}} \cdot 2 \left[ \left( \frac{\partial \bar{u}}{\partial \bar{x}} \right)^2 + \left( \frac{\partial \bar{v}}{\partial \bar{y}} \right)^2 \right] \quad (2-44)$$

where

$$\alpha_\ell = \frac{k_\ell}{\rho_\ell c_{p\ell}} \quad (2-45)$$

so that

$$\frac{D\bar{T}}{D\tau} = \frac{Fo}{Pr} \nabla^2 \bar{T} + \frac{1}{Gr^* Fo} \frac{g \beta_\ell D}{c_{p\ell}} \cdot 2 \left[ \left( \frac{\partial \bar{u}}{\partial \bar{x}} \right)^2 + \left( \frac{\partial \bar{v}}{\partial \bar{y}} \right)^2 \right] \quad (2-46)$$

### Vapor Region:

Conservation of Mass:

$$\frac{\partial \bar{\rho}_v}{\partial \tau} + \frac{\partial \bar{\rho}_v \bar{u}}{\partial \bar{x}} + \frac{\partial \bar{\rho}_v \bar{v}}{\partial \bar{y}} = 0 \quad (2-47)$$

Conservation of Momentum:

$$\frac{D\bar{u}}{D\tau} = \frac{\partial \bar{u}}{\partial \tau} + \bar{u} \frac{\partial \bar{u}}{\partial \bar{x}} + \bar{v} \frac{\partial \bar{u}}{\partial \bar{y}} = - \frac{1}{\bar{\rho}_v} \frac{\partial \bar{p}_m}{\partial \bar{x}} + \frac{\nu_v \theta}{D^2} \nabla^2 \bar{u} \quad (2-48)$$

or

$$\frac{D\bar{u}}{D\tau} = - \frac{1}{\bar{\rho}_v} \frac{\partial \bar{p}_m}{\partial \bar{x}} + Fo \cdot \bar{\mu}_v \cdot \nabla^2 \bar{u} \quad (2-49)$$

$$\frac{D\bar{v}}{D\tau} = \frac{\partial \bar{v}}{\partial \tau} + \bar{u} \frac{\partial \bar{v}}{\partial \bar{x}} + \bar{v} \frac{\partial \bar{v}}{\partial \bar{y}} = - \frac{1}{\bar{\rho}_v} \frac{\partial \bar{p}_m}{\partial \bar{y}} + \frac{\nu_v \theta}{D^2} \nabla^2 \bar{v} + \frac{g \beta_v \theta^2 q''}{k_\ell} \Delta \bar{T} \quad (2-50)$$

or

$$\frac{D\bar{v}}{D\tau} = - \frac{1}{\bar{\rho}_v} \frac{\partial \bar{p}_m}{\partial \bar{y}} + \frac{\bar{\mu}_v}{\bar{\rho}_v} Fo \cdot \nabla^2 \bar{v} + Gr^* Fo^2 \bar{\beta}_v \Delta \bar{T} \quad (2-51)$$

Conservation of Energy:

$$\begin{aligned} \frac{D\bar{T}}{D\tau} = & - \frac{k_\ell}{\rho_\ell c_v} \frac{\theta}{D^2} \frac{D}{D\tau} (\bar{p}_v / \bar{\rho}_v) + \frac{k_\ell \theta}{\rho_\ell c_v} \frac{\theta}{D^2} \frac{1}{\bar{\rho}_v} \frac{D\bar{p}_v}{D\tau} + \frac{k_v \theta}{\rho_\ell c_v D^2} \frac{1}{\bar{\rho}_v} \nabla^2 \bar{T} \\ & + \frac{k_\ell \nu_v}{c_v q'' D \theta} \left\{ 2 \left[ \left( \frac{\partial \bar{u}}{\partial \bar{x}} \right)^2 + \left( \frac{\partial \bar{v}}{\partial \bar{y}} \right)^2 \right] + \left( \frac{\partial \bar{v}}{\partial \bar{x}} + \frac{\partial \bar{u}}{\partial \bar{y}} \right)^2 - \frac{2}{3} \left( \frac{\partial \bar{u}}{\partial \bar{x}} + \frac{\partial \bar{v}}{\partial \bar{y}} \right)^2 \right\} \end{aligned} \quad (2-52)$$

or

$$\begin{aligned} \frac{D\bar{T}}{D\tau} = \frac{Fo}{Pr} \frac{1}{\bar{c}_v} \left[ \frac{D}{D\tau} (\bar{p}_v / \bar{\rho}_v) + \frac{1}{\bar{\rho}_v} \frac{D\bar{p}_v}{D\tau} \right] + \frac{Fo}{Pr} \frac{\bar{k}_v}{\bar{\rho}_v \bar{c}_v} \nabla^2 \bar{T} \\ + \frac{1}{Gr^* Fo} \frac{\bar{\mu}_v}{\bar{\rho}_v \bar{c}_v} \left\{ 2 \left[ \left( \frac{\partial \bar{u}}{\partial \bar{x}} \right)^2 + \left( \frac{\partial \bar{v}}{\partial \bar{y}} \right)^2 \right] + \left( \frac{\partial \bar{v}}{\partial \bar{x}} + \frac{\partial \bar{u}}{\partial \bar{y}} \right)^2 - \frac{2}{3} \left( \frac{\partial \bar{u}}{\partial \bar{x}} + \frac{\partial \bar{v}}{\partial \bar{y}} \right)^2 \right\} \end{aligned} \quad (2-53)$$

### NORMALIZED LIQUID VAPOR INTERFACE BOUNDARY CONDITIONS:

Velocity:

$$\bar{u}_\ell = \bar{u}_v \quad (2-54)$$

$$\bar{v}_{\text{surface}} = \bar{v}_\ell, \quad \bar{v}_v = \bar{v}_{\text{surface}} + \frac{d\bar{y}}{d\tau} \left( \frac{1 - \bar{\rho}_v}{\bar{\rho}_v} \right) \quad (2-55)$$

Temperature:

$$\bar{T}_v = \bar{T}_\ell \quad (2-56)$$

Energy:

$$\left[ \frac{\partial \bar{T}}{\partial \bar{y}} \right]_\ell - \frac{k_v}{k_\ell} \left[ \frac{\partial \bar{T}}{\partial \bar{y}} \right]_v = \frac{\rho_\ell D h_{fg}}{q'' \theta} \frac{d\bar{y}}{d\tau} \quad (2-57)$$

Shear:

$$\left[ \frac{\partial \bar{u}}{\partial \bar{x}} \right]_\ell - \frac{\nu_v}{\nu_\ell} \frac{\bar{\rho}_v}{\bar{\rho}_\ell} \left[ \frac{\partial \bar{u}}{\partial \bar{x}} \right]_v = \frac{q'' \theta}{\rho_\ell \nu_\ell k_\ell} \frac{d\sigma}{d\bar{T}} \frac{d\bar{T}}{d\bar{x}} = Ma^* \frac{Fo}{Pr} \frac{d\bar{T}}{d\bar{x}} \quad (2-58)$$

### NORMALIZED EXTERNAL BOUNDARY CONDITIONS:

Velocity:

$$\bar{u}(0, \bar{y}, \tau) = \bar{v}(0, \bar{y}, \tau) = 0 \quad ; \quad 0 \leq \bar{y} \leq Y/D \quad (2-59)$$

$$\bar{u}(1, \bar{y}, \tau) = \bar{v}(1, \bar{y}, \tau) = 0 \quad ; \quad 0 \leq \bar{y} \leq Y/D \quad (2-60)$$

$$\bar{u}(\bar{x}, 0, \tau) = \bar{v}(\bar{x}, 0, \tau) = 0 \quad ; \quad 0 \leq \bar{x} \leq 1 \quad (2-61)$$

$$\bar{u}(\bar{x}, Y/D, \tau) = \bar{v}(\bar{x}, Y/D, \tau) = 0 \quad ; \quad 0 \leq \bar{x} \leq 1 \quad (2-62)$$

Temperature:

$$\frac{\partial \bar{T}}{\partial \bar{x}}(0, \bar{y}, \tau) = -q''/q'' = 1 \quad ; \quad 0 \leq \bar{y} \leq L \quad (2-63)$$

$$\frac{k_v}{k_l} \frac{\partial \bar{T}}{\partial \bar{x}}(0, \bar{y}, \tau) = \begin{cases} (-q''/q'') = -1 \\ (0/q'') = 0 \end{cases} \quad ; \quad L < \bar{y} \leq Y/D \quad (2-64)$$

$$\frac{\partial \bar{T}}{\partial \bar{x}}(1, \bar{y}, \tau) = q''/q'' = 1 \quad ; \quad 0 \leq \bar{y} \leq L \quad (2-65)$$

$$\frac{k_v}{k_l} \frac{\partial \bar{T}}{\partial \bar{x}}(1, \bar{y}, \tau) = \begin{cases} (q''/q'') = 1 \\ (0/q'') = 0 \end{cases} \quad ; \quad L < \bar{y} \leq Y/D \quad (2-66)$$

$$\frac{\partial \bar{T}}{\partial \bar{y}}(\bar{x}, 0, \tau) = q''/q'' = 1 \quad ; \quad 0 \leq \bar{x} \leq 1 \quad (2-67)$$

$$\frac{k_v}{k_l} \frac{\partial \bar{T}}{\partial \bar{y}}(\bar{x}, Y/D, \tau) = \begin{cases} (q''/q'') = 1 \\ (0/q'') = 0 \end{cases} \quad ; \quad 0 \leq \bar{x} \leq 1 \quad (2-68)$$

NORMALIZED INITIAL CONDITIONS:

$$\bar{T}(\bar{x}, \bar{y}, 0) = \bar{T}_i(\bar{x}, \bar{y}) \quad (2-69)$$

$$\bar{u}(\bar{x}, \bar{y}, 0) = 0 \quad (2-70)$$

$$\bar{v}(\bar{x}, \bar{y}, 0) = 0 \quad (2-71)$$

$$\bar{p}(\bar{x}, \bar{y}, 0) = \bar{p}_i(\bar{x}, \bar{y}, 0) \quad (2-72)$$

## 2.5 RESULTING DIMENSIONLESS PARAMETERS

The dimensionless coefficients associated with the terms in the differential equations and boundary conditions are dimensionless parameters. Some of these coefficients include more than one of the dimensionless groups. When this is the case, the group is broken into more familiar subgroups, each of which are also dimensionless. The resulting set of dimensionless groups, along with their original forms, are presented in Table 2-1.

Since it is not possible to scale two tanks while satisfying all the independent dimensionless groups,  $Gr^*$ ,  $Fo$ ,  $I$ ,  $Ma^*$ ,  $Pr$  and  $c_p/g\beta_l D$ , two were eliminated. The first was the Marangoni number associated with motion at the liquid vapor interface resulting from surface tension changes with temperature. Since little variation in temperature along the interface was expected, and because no such motion was ever observed during flow visualization experiments with Freon 113 conducted earlier at McDonnell Douglas, the Marangoni number was not kept. The other pi-group,  $c_p/g\beta_l D$ , was eliminated since it is associated with the viscous dissipation term in the energy equation and is assumed to have a negligible effect during stratification. Table 2-2 gives the resulting set of dimensionless scaling groups that were used in this study. The dimensionless property ratios were all satisfied since the scaling tests were conducted with a single fluid.

Table 2-1  
DIMENSIONLESS COEFFICIENTS

Dimensionless Group From Differential Equations	Equation	Independent Dimensionless Groups	Remarks
$\frac{\mu_l \theta}{\rho_l D^2}$	Momentum - Liquid	$= Fo$	$Fo =$ Fourier no.
$\frac{g \beta_l \theta^2 q''}{k_l}$	Momentum - Liquid	$= \frac{g \beta_l q'' D^4}{k_l \nu_l^2} Fo^2 = Gr^* Fo^2$	$Gr^* =$ Modified Grashof no.
$\frac{k_l \mu_l}{\rho_l q'' D c_{p_l} \theta}$	Energy - Liquid	$= Gr^* Fo \frac{\beta_l g D}{c_{p_l}}$	$\frac{\beta_l g D}{c_{p_l}}$ required if viscous heating is important
$\frac{\mu_v \theta}{\rho_l D^2}$	Momentum Vapor	$= \frac{\mu_v}{\mu_l} Fo$	
$\frac{g \beta_v \theta^2 q''}{k_l}$	Momentum- Vapor	$= Gr^* Fo^2 \frac{\beta_v}{\beta_l}$	
$\frac{k_v \theta}{\rho_l c_v D^2}$	Energy- Vapor	$= \frac{k_v}{k_l} \frac{c_{p_l}}{c_v} \frac{Fo}{Pr}$	$Pr = \frac{\mu c_p}{k} = \frac{\nu}{\alpha}$ , where $\alpha = \frac{k}{\rho c_p}$
$\frac{k_l \mu_v}{\rho_l c_v q'' \theta D}$	Energy - Vapor	$= \frac{\mu_v}{\mu_l} \frac{c_{p_l}}{c_v} \frac{1}{Gr^* Fo} \frac{g \beta_l D}{c_{p_l}}$	$\frac{\beta_l g D}{c_{p_l}}$ required if viscous heating is important
$\frac{q'' \theta}{\mu_l k_l} \frac{d\sigma}{dT}$	Liquid - Vapor Interface	$= \frac{Fo}{Pr} \frac{q'' D^2}{\mu_l k_l \alpha} \frac{d\sigma}{dT}$	$Ma^* = \frac{q'' D^2}{\mu_l k_l \alpha} \frac{d\sigma}{dT} =$ Marangoni no.
$\frac{h_{fg} \rho_l D}{q'' \theta}$	Liquid - Vapor Interface	$= \frac{Pr}{Fo} \frac{h_{fg} k_l}{q'' D c_{p_l}} = \frac{Pr}{Fo} ;$	$\frac{h_{fg} k_l}{q'' D c_{p_l}} =$ Interface no. $= I$

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Table 2-2

SCALING GROUPS FOR THE COMPONENT, TWO-PHASE  
SYSTEM WITH A FLAT INTERFACE

Parameter	Requirement When Same Fluid Used for Model and Prototype
$Fr = \frac{\mu_l \theta}{\rho_l D^2}$	$\frac{\theta}{D^2} \Big _{\text{model}} = \frac{\theta}{D^2} \Big _{\text{prototype}}$
$Gr^* = \frac{g \beta_l q'' D^4 \rho_l^2}{k_l \mu_l^2}$	$g q'' D^4 \Big _{\text{model}} = g q'' D^4 \Big _{\text{prototype}}$
$Pr = \frac{\mu_l^c p_l}{k_l}$	Satisfied
$\frac{\mu_v}{\mu_l}$	Satisfied
$\frac{\beta_v}{\beta_l}$	Satisfied
$\frac{c_{p_l}}{c_v}$	Satisfied
$\frac{k_v}{k_l}$	Satisfied
$\frac{\rho_v(t/\theta)}{\rho_l}$	Satisfied
$\frac{q'' D c_p}{h_{fg} k_l}$	$qD \Big _{\text{model}} = qD \Big _{\text{prototype}}$

### Section 3

## EXPERIMENTAL EQUIPMENT AND INSTRUMENTATION

### 3.1 INTRODUCTION

The stratification and destratification experiments were conducted with a thermal system specifically designed for that purpose. The experimental system included three test tanks capable of supplying heat through the walls, a centrifuge facility for high-g tests, and the instrumentation necessary to regulate and monitor the experiment.

The test tank included segmented blanket heaters covering the entire external surface of the tank and encapsulated by foam insulation. Thermocouples were used in the liquid, on the tank walls, on tank heat shorts (penetrations), and in the insulation to monitor the temperatures. In addition, a centrifugal pump was used for the destratification subsystem. The MDAC Santa Monica centrifuge facility was used for the high-g experiments and was necessary to achieve the same Grashof number for scaling the 6 inch diameter tank to the 12 inch and 18 inch diameter tanks. The test liquid, Freon 113, was selected after evaluating a substantial number of candidate liquids.

There were five major instrumentation components.

1. Thermocouples for obtaining temperatures.
2. A pressure transducer.
3. A flow meter for monitoring the destratification jet velocity.
4. A variable power supply for each heater blanket.
5. A centrifuge facility for producing the high-g levels required.

Each of these items will be discussed further in the following subsections.

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## 3.2 TEST TANK

### 3.2.1 Basic Design

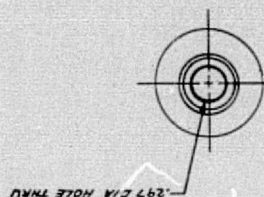
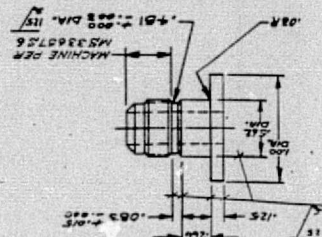
The baseline Modular Nuclear Vehicle (MNV) and Saturn S-IVB-203 was selected as a typical tank and provided the general guideline for establishing tank geometry, tank dimensions, and the thermal properties associated with the test tanks. Hence, the test tank was a right circular cylinder with hemispherical dome caps on each end of the cylinder. Destratification system design is less well established so that the mixing system was designed as simply as possible using a system somewhat similar to that used in the early basic destratification experiments conducted at General Dynamics (2, 3).

Three similar tanks of different dimensions were selected for the experiments since a single fluid was used. These three tanks in conjunction with the centrifuge facility were required for the preservation of the dimensionless parameters needed for similarity. These test tanks were fabricated from 347 stainless steel with diameters of 6, 12, and 18 inches. The length of the tanks were 18, 36, and 54 inches, respectively, giving a length to diameter ratio of 3 for each. A detailed design drawing for the 6 in. diameter tank is shown in Figure 3-1. The dimensions shown were multiplied by a factor of 2 and 3 for the 12 in. and 18 in. diameter tanks, respectively. The tanks were fabricated and designed to maintain geometric and thermodynamic similarity to satisfy the scaling parameters listed in Table 2-2. In addition to the scaling of the external dimensions, all wire diameters, wire insulation thicknesses, foam insulation, and wall thicknesses were scaled.

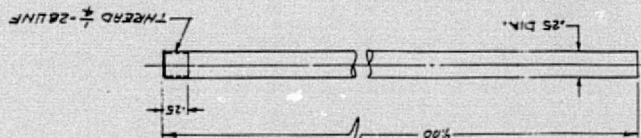
It should be noted that the tank design using flanges at the junction of the hemispherical ends and the cylindrical section increases the versatility of the apparatus for further tests without compromising this study. In addition to allowing convenient access to the interior of the tanks to repair or relocate instrumentation, and to adjust the simulated jet mixing device, the tank end configurations could be altered by simply constructing new end sections and attaching them to the standard cylindrical section. The design also allows the ends to be connected to form a spherical test tank, with the cylindrical

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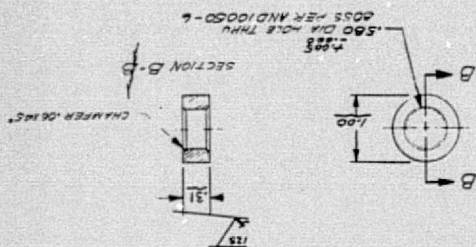
DETAIL - 29 ADAPTER ②



DETAIL - 51 ④



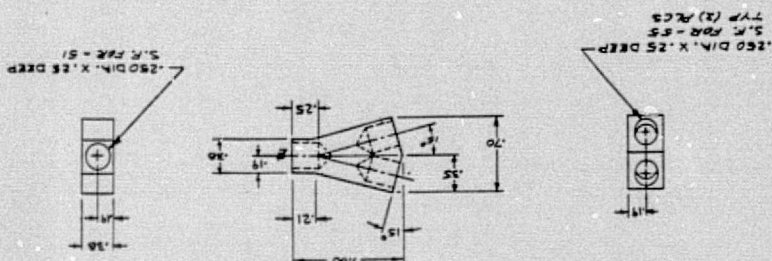
DETAIL - 23 BUSH ②



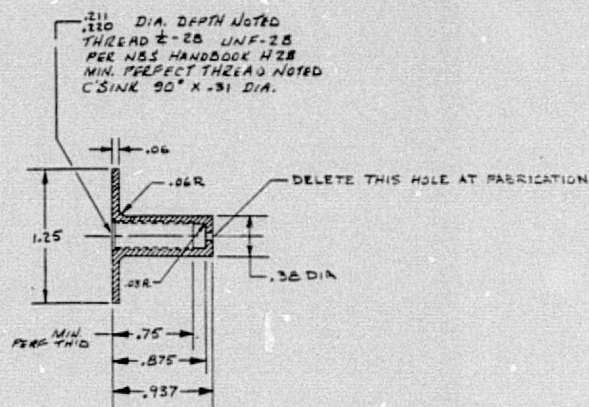
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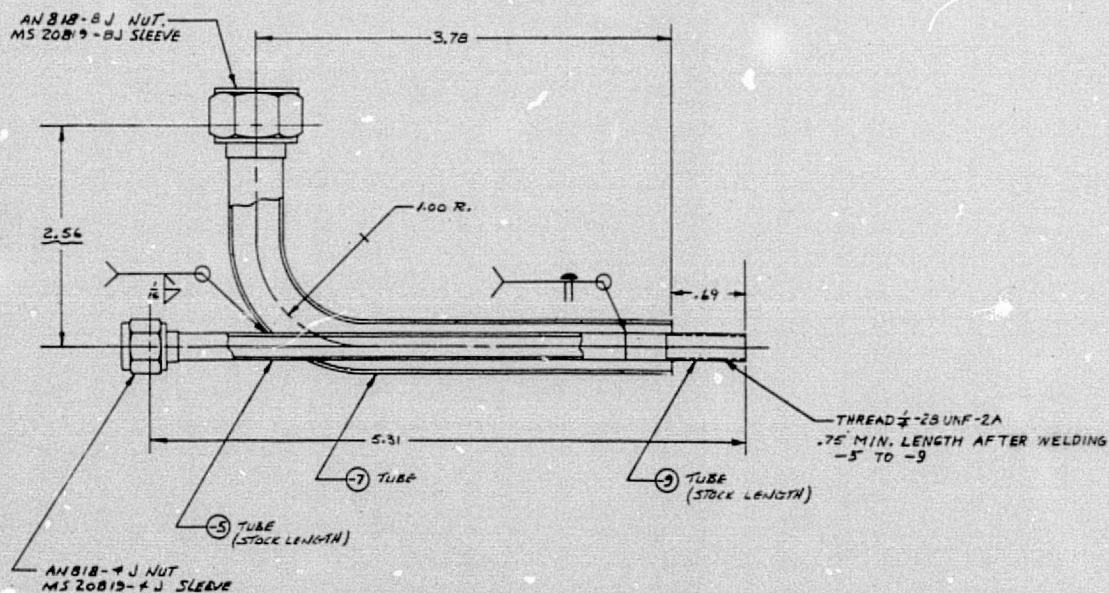
DETAIL - 53 ④



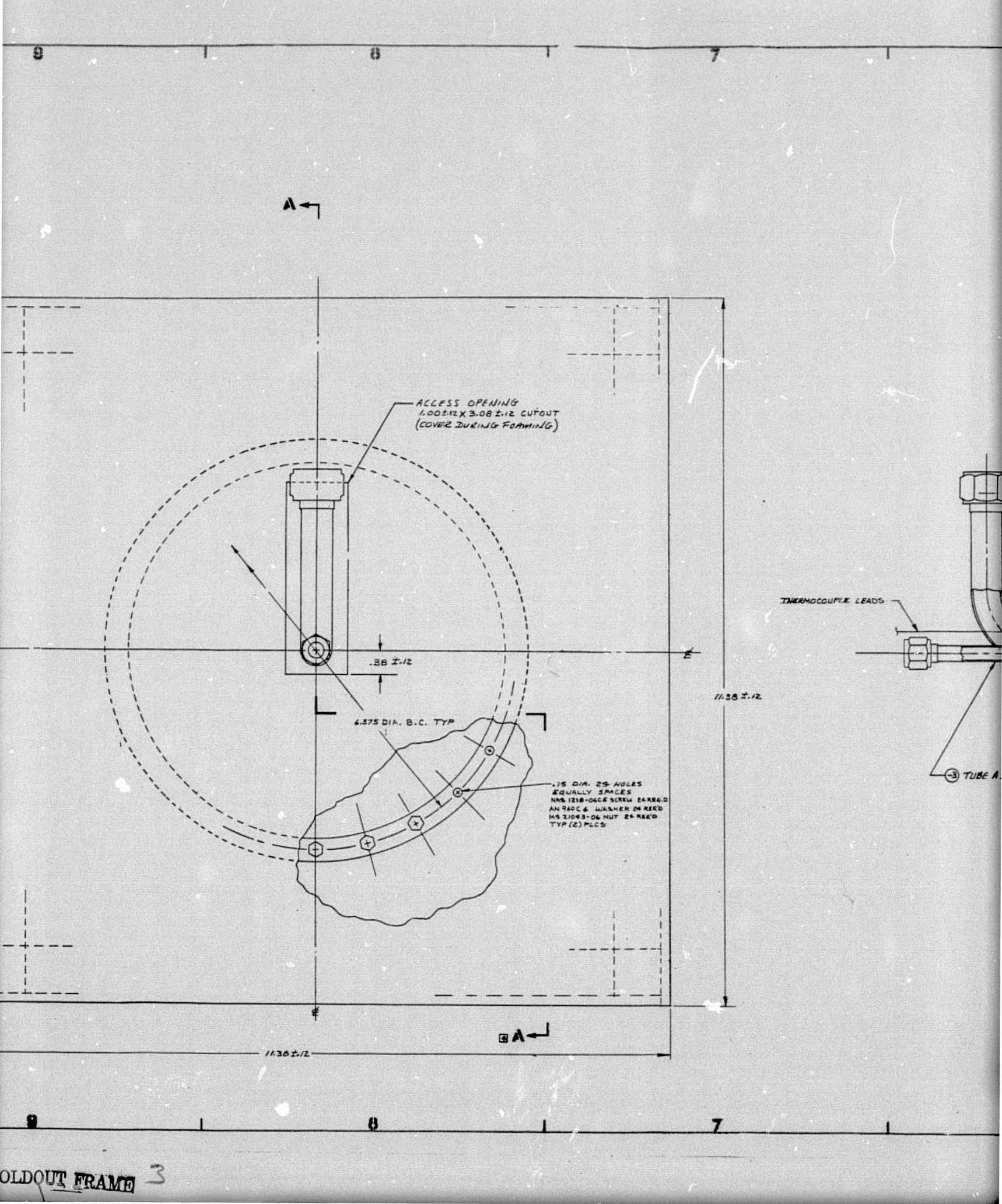




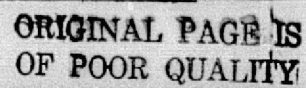
DETAIL OF -17 ORIFICE **A**  
 ALL MACHINE SURFACES 125 FINISH



DETAIL OF -3 TUBE ASSEMBLY **B**  
 FLARE TUBES PER MS 33594









**Figure 3-1**



section removed. All of these alterations could be accomplished while maintaining the geometric similarity between test tanks. Figure 3-2 is a photograph of these tanks.

### 3.2.2 Test Tank Heaters

An electrical heater blanket covering the entire tank was used for generating the various wall heat-flux values in the stratification experiments. The blanket made by embedding a resistance wire mesh into a thin silicone rubber sheet was produced by Electrofilm Inc., North Hollywood, Calif.

Ten heater blankets, each with separate electrical leads, were employed and had the capability to heat any part of the container, if desired. Thus, liquid heating, ullage heating, or a combination of the two could be achieved with this apparatus. Figure 3-3 shows the heater blanket arrangement; in this study the two heater sections at each elevation were wired in parallel to serve as one heater. This resulted in five separate heater circuits. The heater blankets used on all three tanks were capable of producing a maximum of 10 watts/in.<sup>2</sup> (4,910 Btu/hr-ft<sup>2</sup>). The blankets are shown in Figure 3-2.

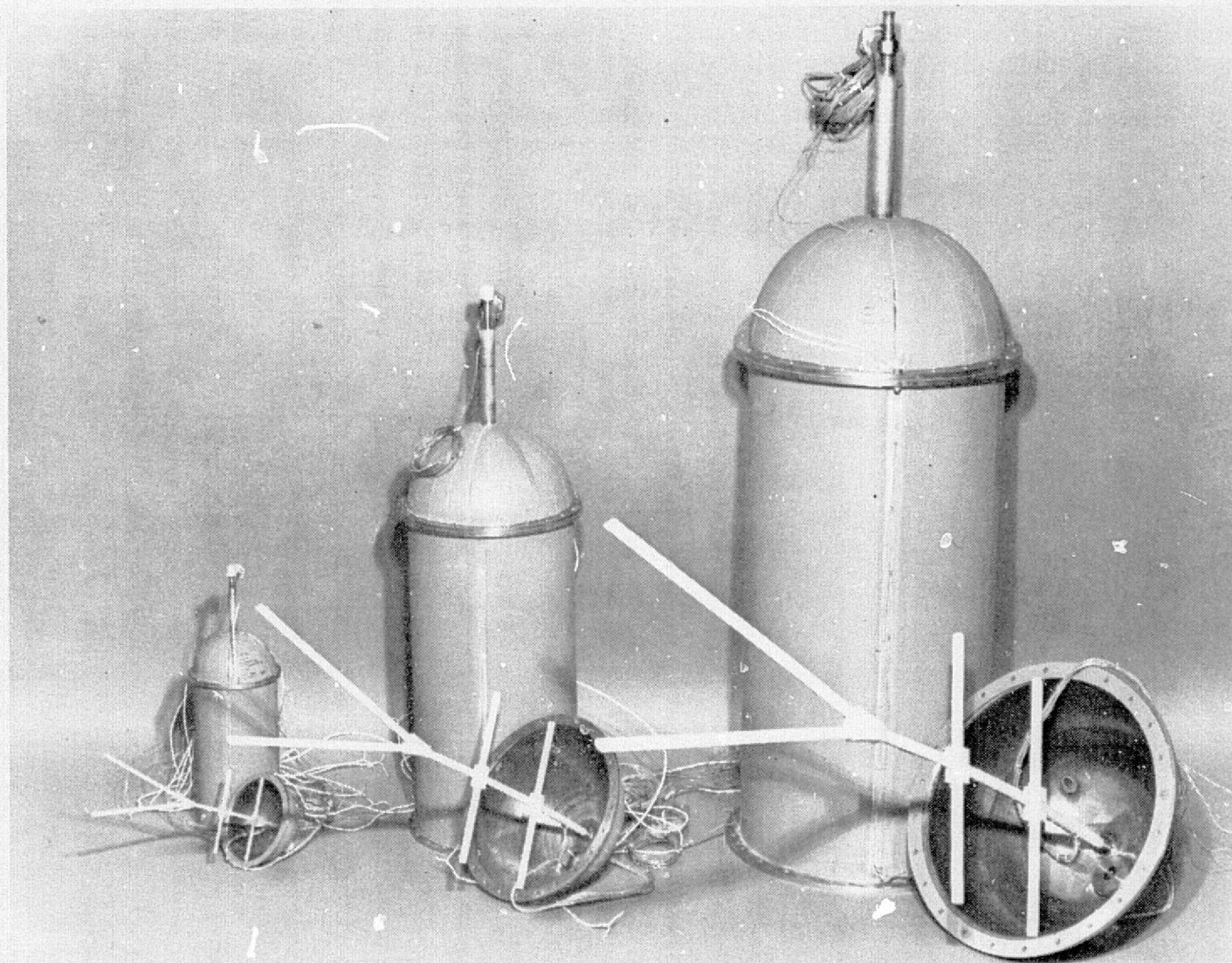
### 3.2.3 Test Tank Insulation

Polyurethane foam was selected for the test-tank insulation because of its low thermal conductivity (0.01 Btu/hr-ft<sup>0</sup>F), its relatively high maximum operating temperature (300<sup>0</sup>F), and because it could be foamed in place and is rigid after curing. The tanks and the heaters were essentially encapsulated within the foam. This was accomplished by placing the tank in a plywood box and filling the void between the tank and the box walls with foam. In this manner the plywood box became the protective covering, allowing for easy handling of the tank and providing a mounting platform for the tank during the stratification experiments. In addition, since the foam itself provided the structural support for the tank, heat short problems due to structural members attached directly to the tank were eliminated. Figure 3-4 shows the tank encapsulated by the foam in the plywood box.

### 3.2.4 Destratification System

The basic purpose of the destratification system was to mechanically and thermally mix the cold liquid near the tank bottom with the warmer liquid

FIGURE 3-2  
6 IN., 12 IN., AND 18 IN. DIAMETER SCALING TANKS



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FIGURE 3-3  
WALL HEATER ARRANGEMENT

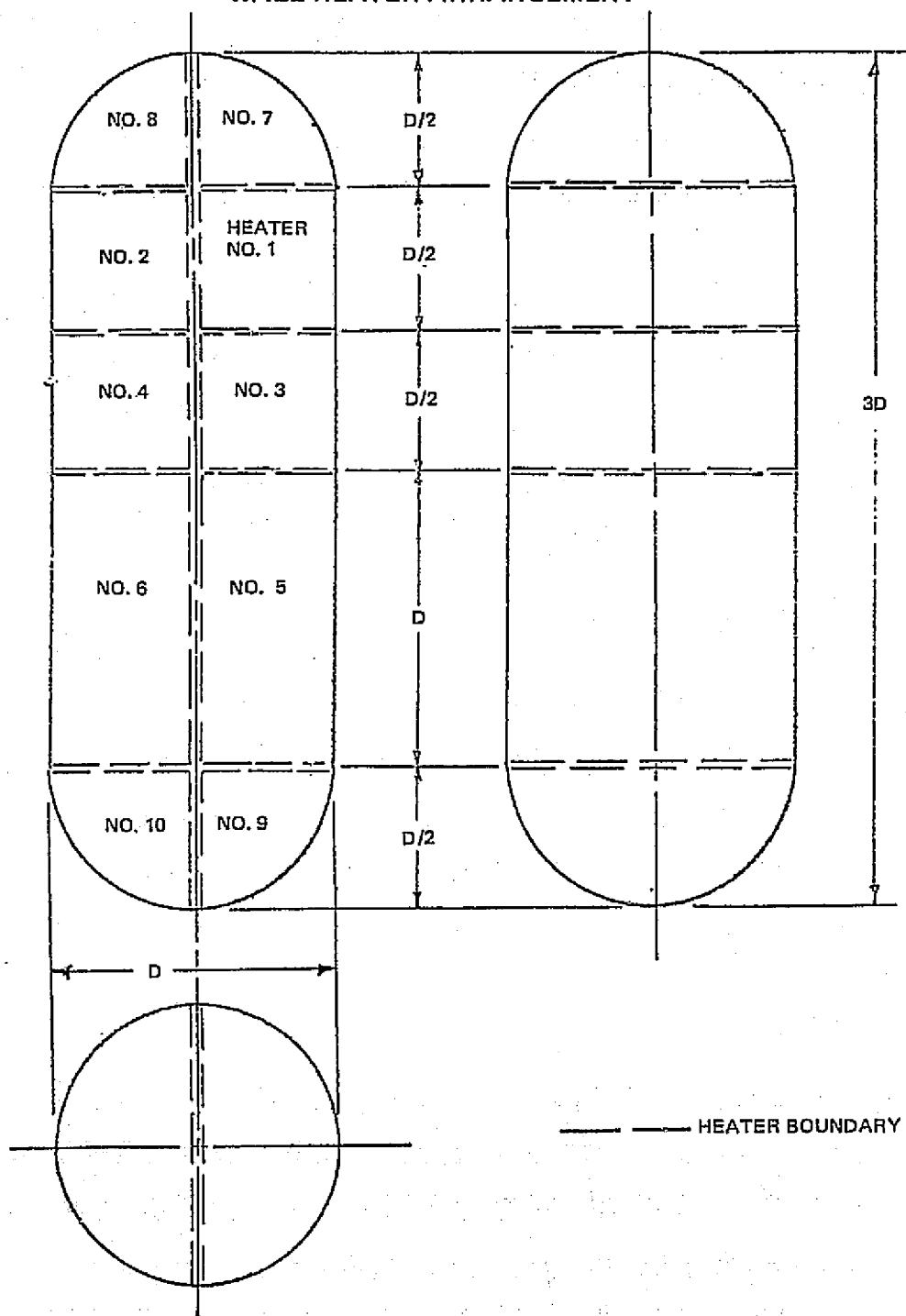
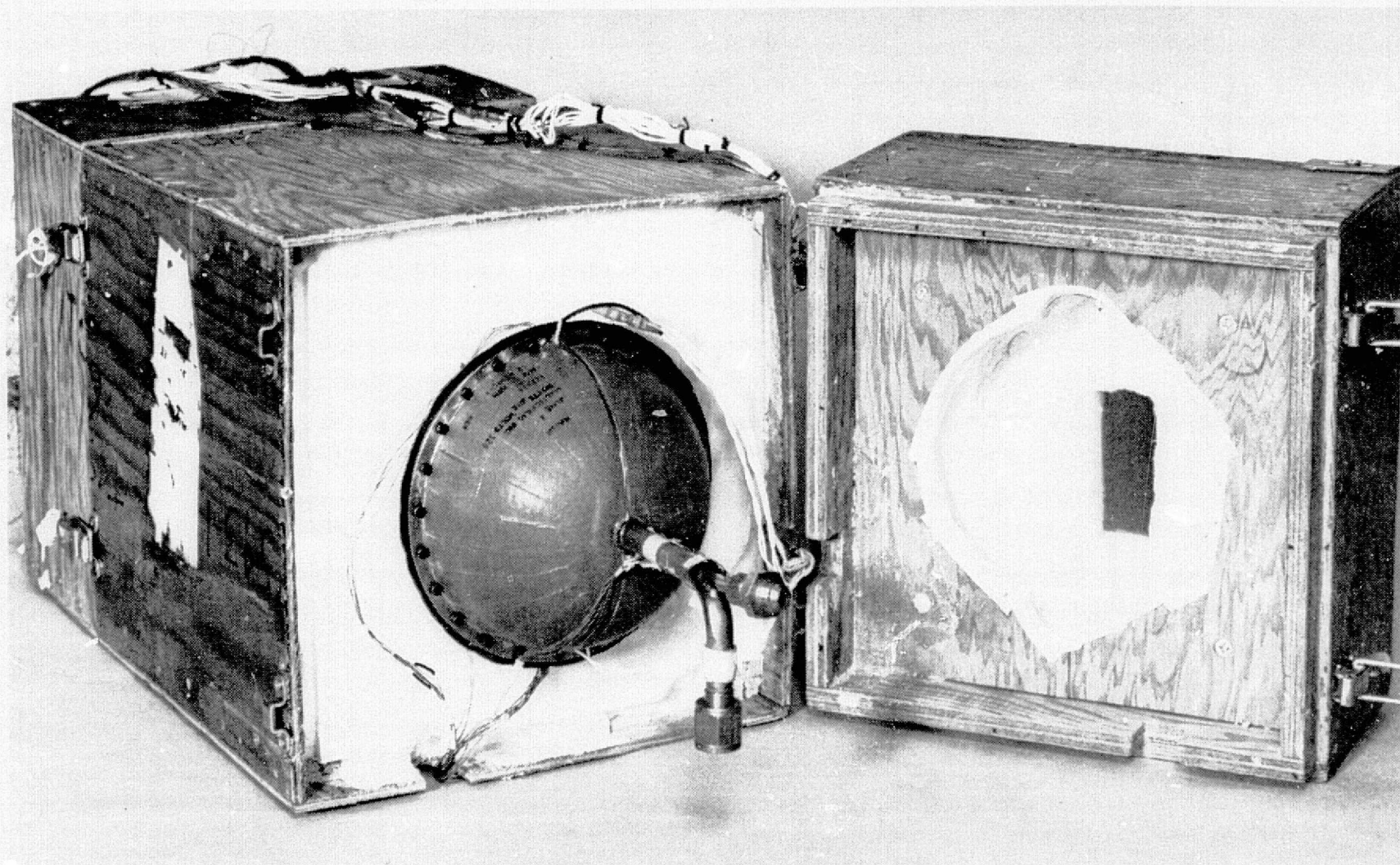




FIGURE 3-4  
FOAM ENCAPSULATED TEST TANK



above it to study its effect on the tank pressure. An axially directed nozzle located in the bottom of the tank and connected to the outlet of the centrifugal pump was used to circulate the cold liquid up through the warmer liquid region. An inlet, concentric to the nozzle and leading to the pump inlet, provided for the closed-fluid loop that resulted when the pump was operating. In this manner, the cooler liquid along the bottom was fed into the pump and exited as a cold jet of liquid moving upward into the warmer liquid. Figure 3-5 is a sketch of this flow loop.

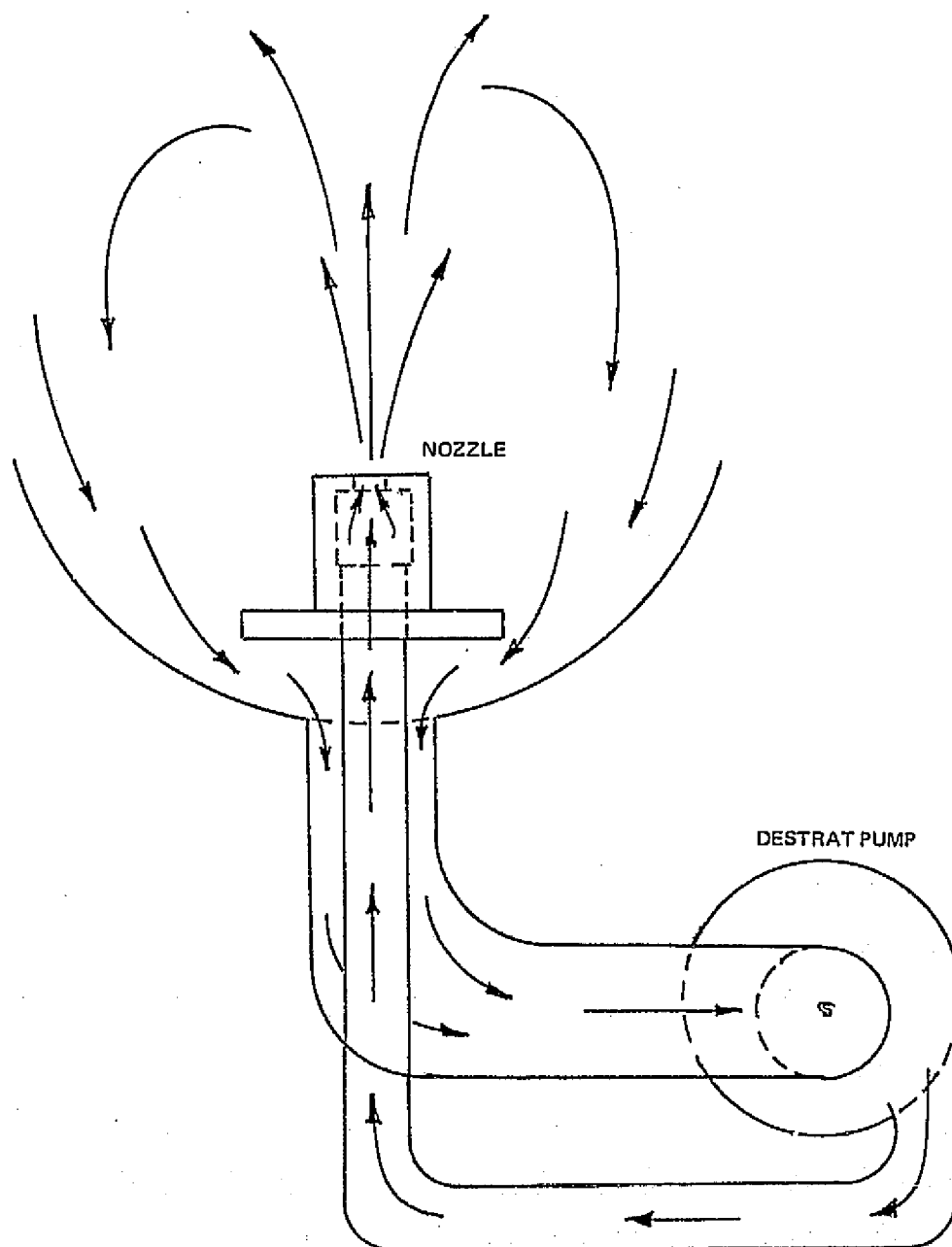
The nozzle openings for each of the tanks were scaled in the same manner as the tanks. The nozzle openings for the 6, 12, and 18 inch diameter tanks are 0.0625, 0.125, and 0.1875 inches in diameter, respectively. The inlet and outlet tubes protruding from the tank were also scaled. Exact scaling was not maintained with the external piping which connected the pump to the tank. However, the size and length of this plumbing increased approximately in proportion with increasing tank size. All of the external piping was wrapped in fiber glass insulation to reduce the heat loss to the surroundings as the heated liquid was circulated through the pump. An Eastern 1/15-hp centrifugal pump was used for all three tanks. The flow rate for this pump was regulated with a Superior Electric Co., 7.5 amp, Powerstat.

### 3.3 INSTRUMENTATION

#### 3.3.1 Thermocouples

A large number of thermocouples were necessary for the stratification study to accurately assess all of the transient thermal changes that occur during the heating and destratification periods. Thermocouples were used to measure the temperature distribution within the liquid and vapor, and to monitor the heat stored in and/or lost through the tank walls, insulation, and the heat shorts. The wall and insulation measurements were needed to determine the energy stored and hence to provide a reasonably accurate estimate of the actual heat flux to the liquid in the tank. However, the number of thermocouples was limited by the instrumentation, and by the risk of the thermocouple rake interference with the convection currents produced by the destratification pump. A flow visualization study with a plexiglass

FIGURE 3-5  
DESTRATIFICATION FLOW LOOP



tank and several thermocouple rake configurations was conducted to find the rake which had the least influence on the destratification pump flow patterns.

Figure 3-6 is a schematic of the rake selected and the thermocouple locations. The two cross members allow for the radial temperature distribution at two levels. These rakes are also shown in the photograph of Figure 3-4. A total of 37 thermocouples are on the rake. The liquid and ullage thermocouple locations relative to the tank height are given in Table 3-1. Figure 3-7 shows the thermocouple attachment points on the tank walls as well as on penetrations and within the foam insulation. A total of 40 thermocouples were used to monitor the wall and penetration temperatures.

The thermocouples were made from gauge number 36, 30, and 26 copper constantan wire for the 6, 12, and 18 inch diameter tanks. Two, 50-terminal Research, Incorporated, 150 °F thermocouple reference junction ovens were used with the thermocouples. The output of the 77 thermocouples was handled with a Hewlett Packard 2010B Data Acquisition System. A 2911B Hewlett Packard Crossbar Scanner Control was used to scan and print out all 77 voltage values in less than 15 seconds. The thermocouple signal was amplified with a Dymec Guarded Data Amplifier and then sent to the Hewlett Packard 2401-C Integrating Digital Voltmeter. The voltages were printed with a Hewlett Packard Model J66-562A Digital Recorder. The scanner was linked to a Hewlett Packard digital clock so that a scan frequency could be determined and set prior to the test period. This data acquisition system is shown in Figure 3-8. A schematic for the entire test arrangement is shown in Figure 3-9.

### 3.3.2 Tank Pressure

The tank internal pressure was monitored and recorded along with the thermocouple data. A pressure transducer, located at the top of the tank, also had its output signals recorded in the Data Acquisition System. A Statham 0 to 50 psia, 7-volt, maximum-pressure transducer was used for the automatic monitoring of the pressure. A Trygon Electronics Model HR-20-16A Power Supply was used with this transducer. Observation of the pressure history

FIGURE 3-6  
LIQUID-ULLAGE RATE - THERMOCOUPLE LOCATIONS

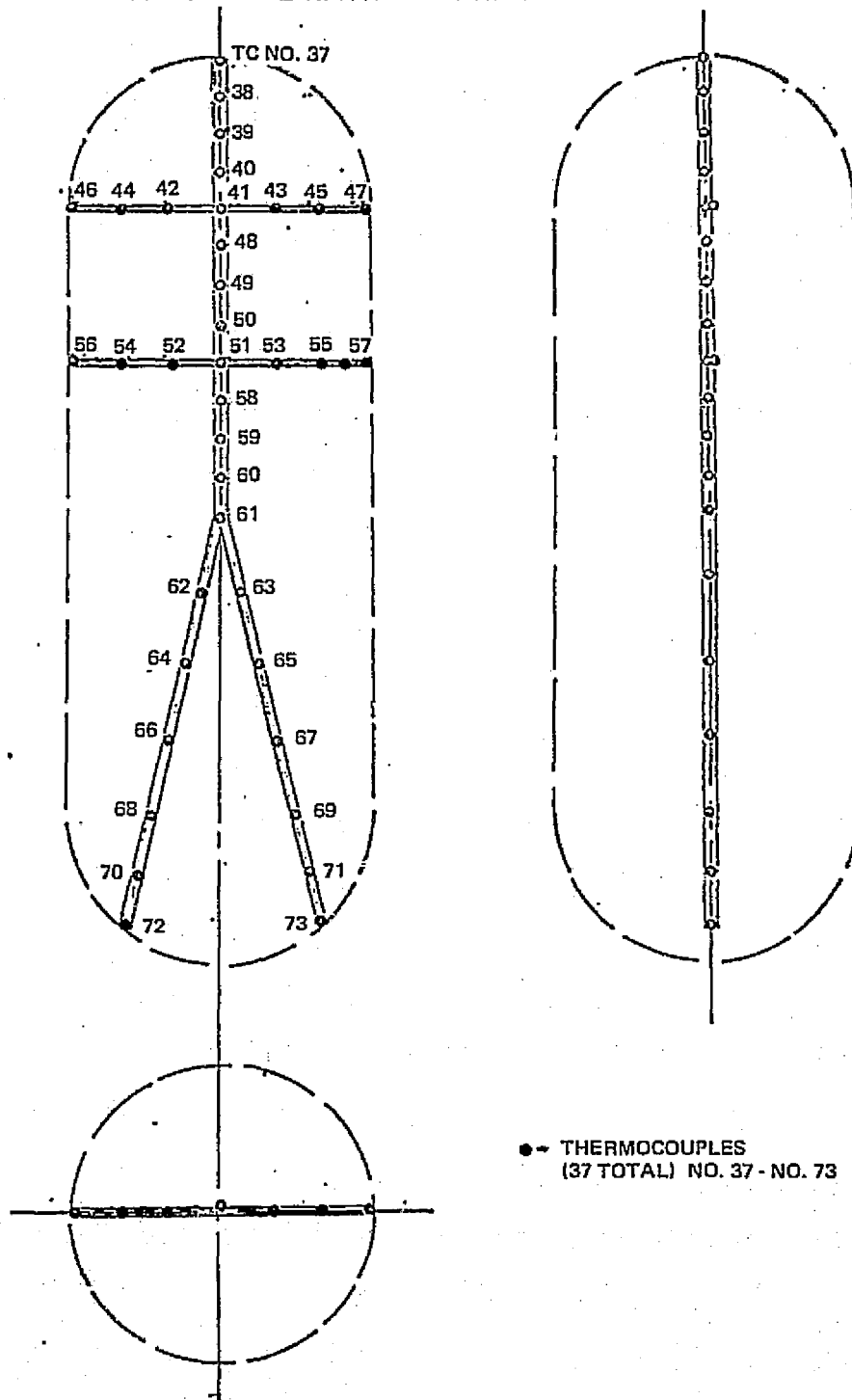




Table 3-1

## LIQUID-ULLAGE THERMOCOUPLE - NORMALIZED TANK HEIGHT RATIOS

Thermocouple No.	Normalized Tank Height (y/Y)
37	0.98
38	0.958
39	0.917
40	0.875
41-47	0.833
48	0.793
49	0.752
50	0.71
51-57	0.668
58	0.626
59	0.584
60	0.542
61	0.5
62-63	0.42
64-65	0.339
66-67	0.259
68-69	0.178
70-71	0.111
72-73	0.044

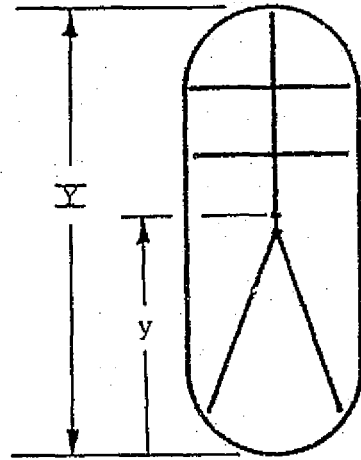


FIGURE 3-7  
TANK WALL AND PENETRATION THERMOCOUPLE LOCATIONS

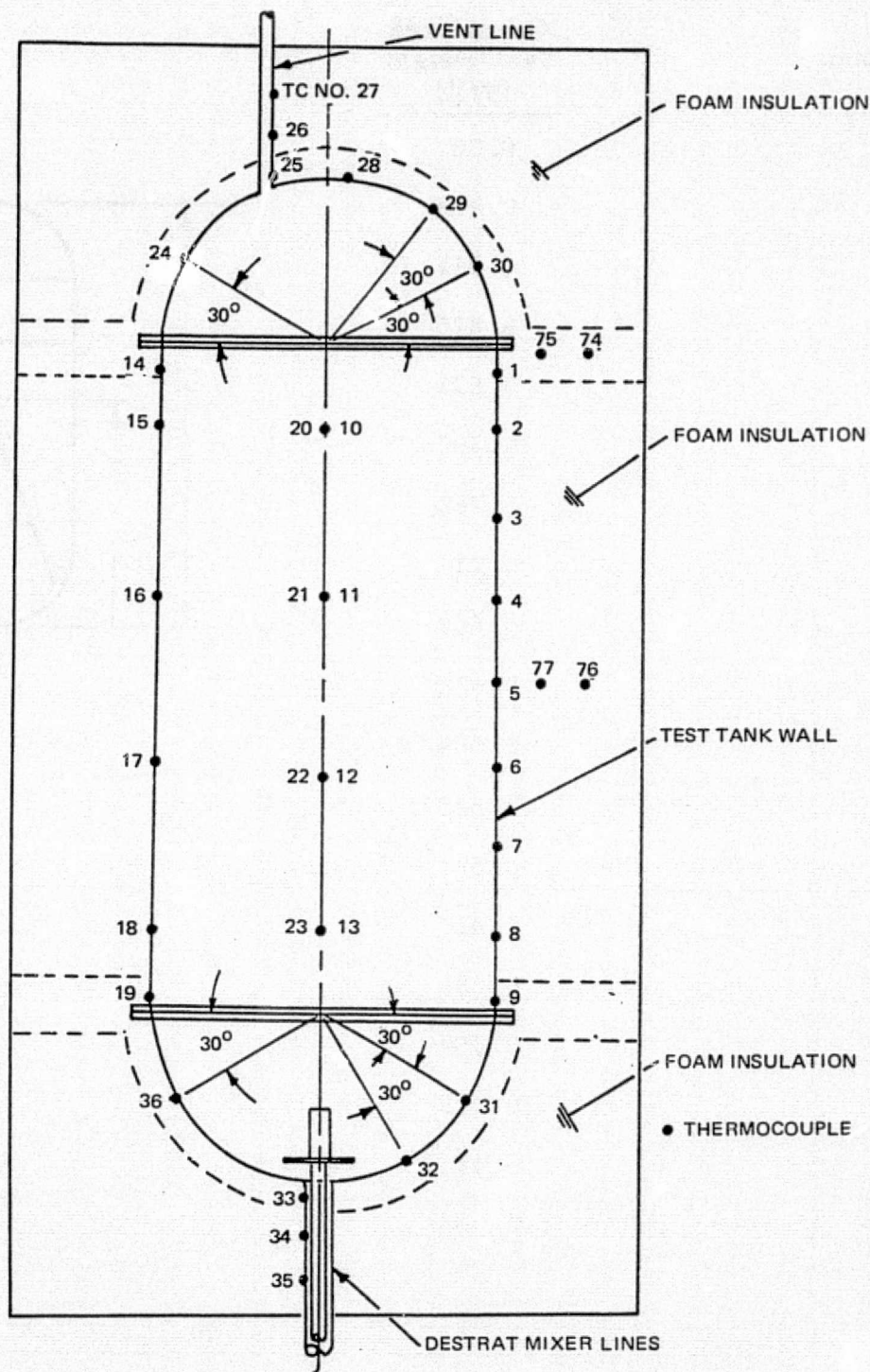


FIGURE 3-8  
DATA ACQUISITION SYSTEM

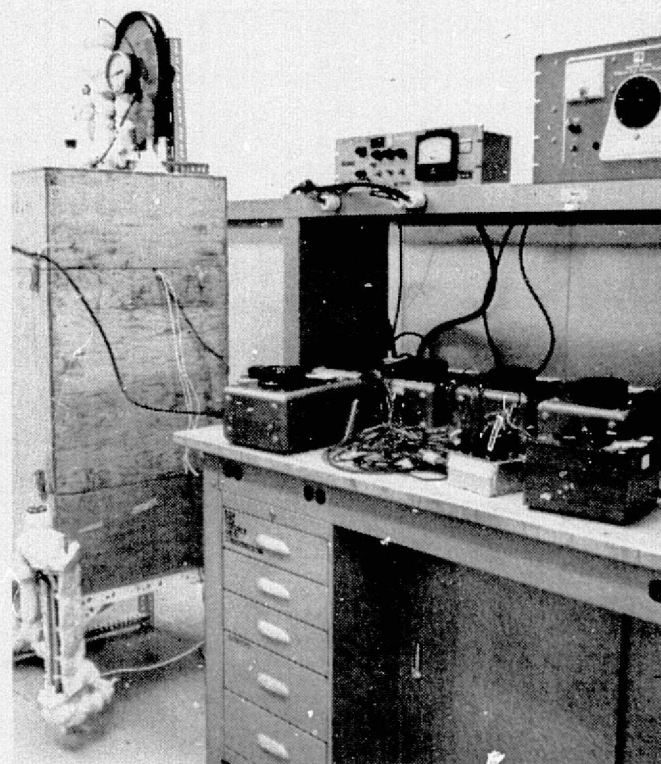
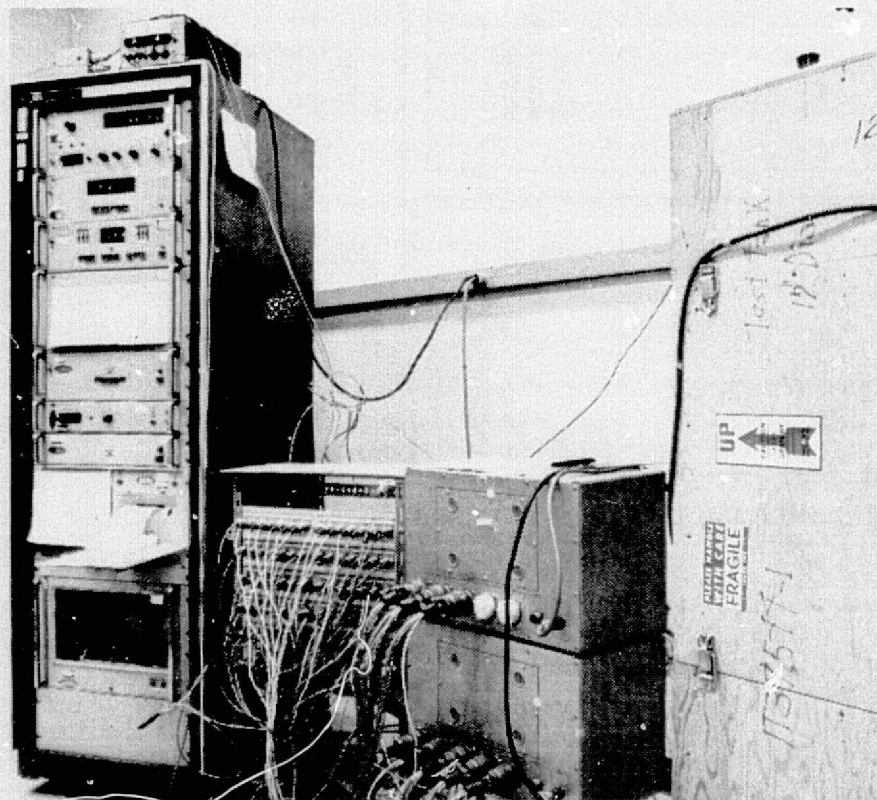
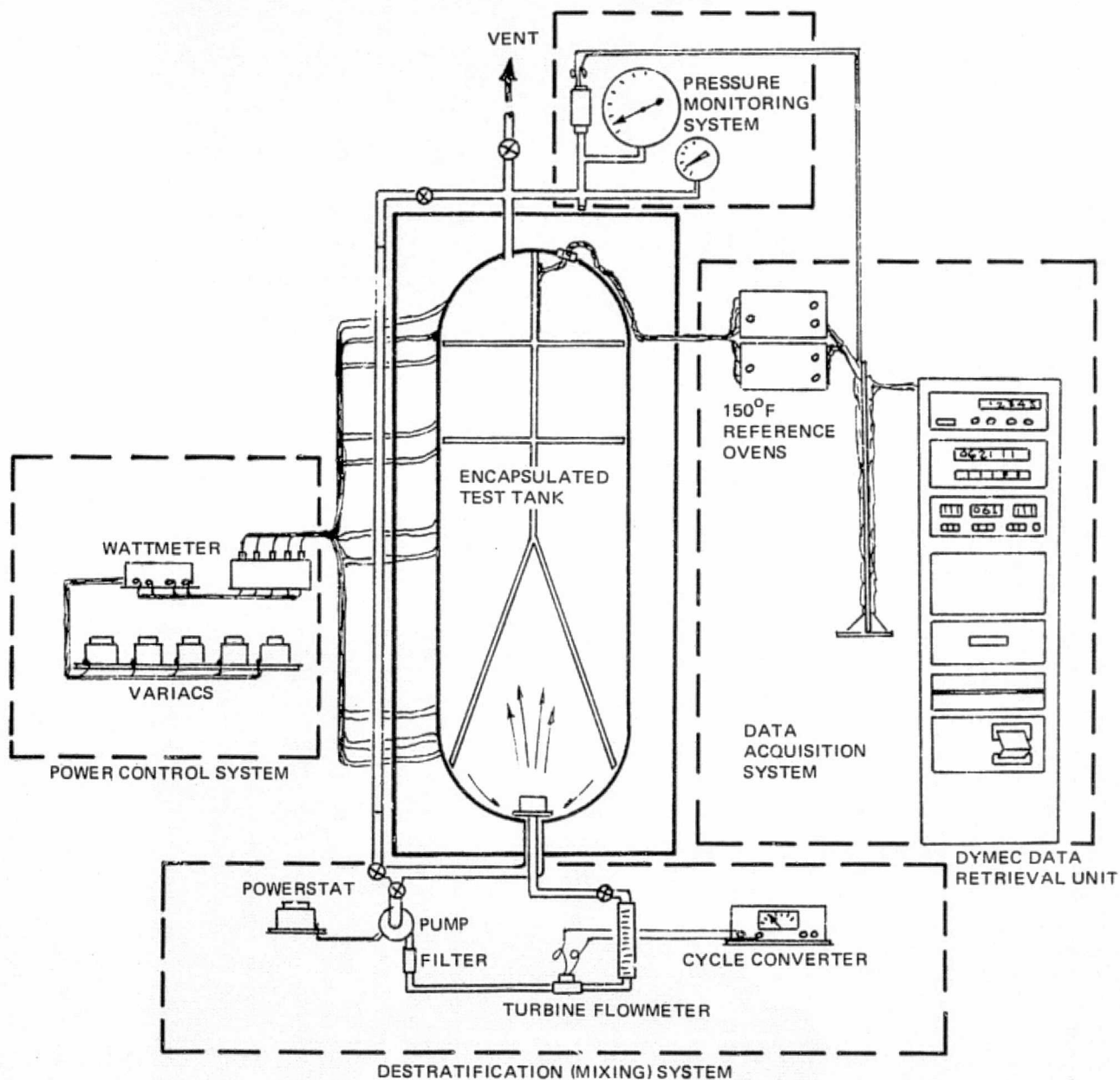


FIGURE 3-9  
SCHEMATIC TEST SETUP



with a visual pressure gage was made along with the transducer recordings. The visual pressure gage used for the 1G tests was a Seegers Precision Pressure Transfer Standard, marked in 0.10 psia subdivisions.

### 3.3.3 Blanket Heater Power

The blanket heaters were simple electrical resistance heaters. The five heater pairs (1-2, 3-4, 5-6, 7-8, 9-10) were operated separately, each using a General Radio Type W20MT3 20 amp Variac to regulate the voltage in a continuous manner. The power for each heater segment was measured with a Singer Single-Phase, Low-Power Factor Wattmeter, model DLW, with a range from 150 to 1,200 watts. For the experiments where the power exceeded 1,200 watts, a separate ammeter and voltmeter were used to measure the power output.

### 3.3.4 Flow Meter for Destratification Pump

The mass flow rate of the destratification jet was monitored by measuring the volumetric flow rate of the Freon on the outlet side of the destratification pump. A Waugh Turbine Flow Meter (Instrument No. 101877-102-1327) with a flow range from 0.15 to 1.5 gpm was used. The output of the flowmeter was fed into a Waugh Pulse Rate Converter, Model RF-213. Frequency values from the converter were then translated into flow rate values.

## 3.4 SIMULANT LIQUID SELECTION

The first stage of the screening process considered 40 noncryogenic liquids and Reference 4 documents that process in detail. The criteria considered to be important for scaling tests with a single fluid were:

- A. Boiling point of the liquid.
- B. Ease of handling.
- C. Availability of precise property data.
- D. Cryogenic propellant similarity.

The boiling point of the liquid was an important consideration since a liquid which boils near room temperature would cause fewer problems in general. For example, a low boiling point results in less heat loss to the surroundings, make handling easier (as well as test control), and also makes it easier to



reach an isothermal condition. In addition, it is convenient to have the room temperature and saturation temperatures close together. This reduces the time between experiments whenever the tank must be heated or cooled down to the saturation temperature. The availability of accurate property data was mandatory to interpret the experimental results.

Table 3-2 lists some of the readily available liquids with boiling points between 94.3°F and 231°F. Flammability and toxicity were also considered to be important factors along with availability. As a result, Freon 113 PCA (i. e., Precision Cleaning Agent) was selected as the liquid best suited for this program. The boiling point of Freon 113 is approximately 117°F and as a result does not cause burns when it contacts the skin. Freon 113 is also a relatively safe liquid to use with proper ventilation. Threshold limit values (TLV) adopted by the American Conference of Governmental Industrial Hygienists provided a guide to the toxicity of solvents and other substances. These limits in ppm of air for Freon are the same as for ethyl alcohol and acetone and are at the highest TLV for any material with the exception of carbon dioxide. In addition, the fluorocarbon solvent vapors are completely nonflammable. The Freon 113, also labeled as Precision Cleaning Agent (PCA), is relatively pure thereby minimizing solid deposition within the tank since makeup liquid was required after each test.

### 3.5 CENTRIFUGE FACILITY

The MDAC-W 36-ft-diameter centrifuge facility was used in this study to obtain the 8-g and 27-g environments for the thermal stratification tests. The large centrifuge was used to minimize the gravity gradient across the 6 inch tank. This is the result of the fact that the acceleration due to rotation is  $r\omega^2$ . Because of the 18 ft arm and the 18 inch tank length, the change in the g level along the tank axis is approximately 10 percent. The tests were performed with the 6 inch tank using the same instrumentation that was used on the 12 and 18 inch tanks 1-g environment tests.

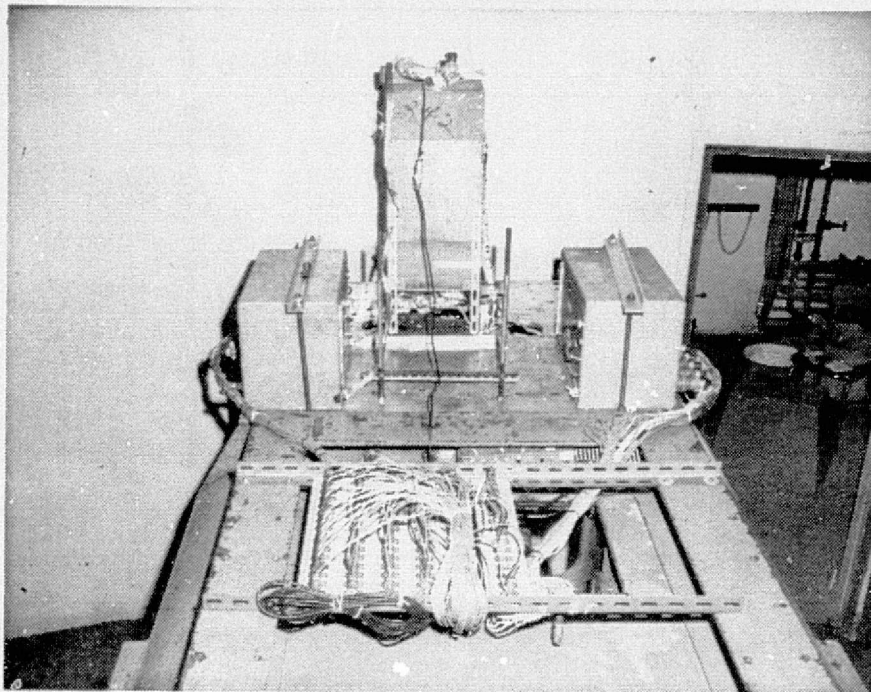
The centrifuge was equipped with slip rings to permit application of electric power for heating the test tanks and monitoring the thermal effects in the test fluid. Figure 3-10 shows the tank mounted on the centrifuge.

Table 3-2  
CANDIDATE FLUID BOILING POINTS

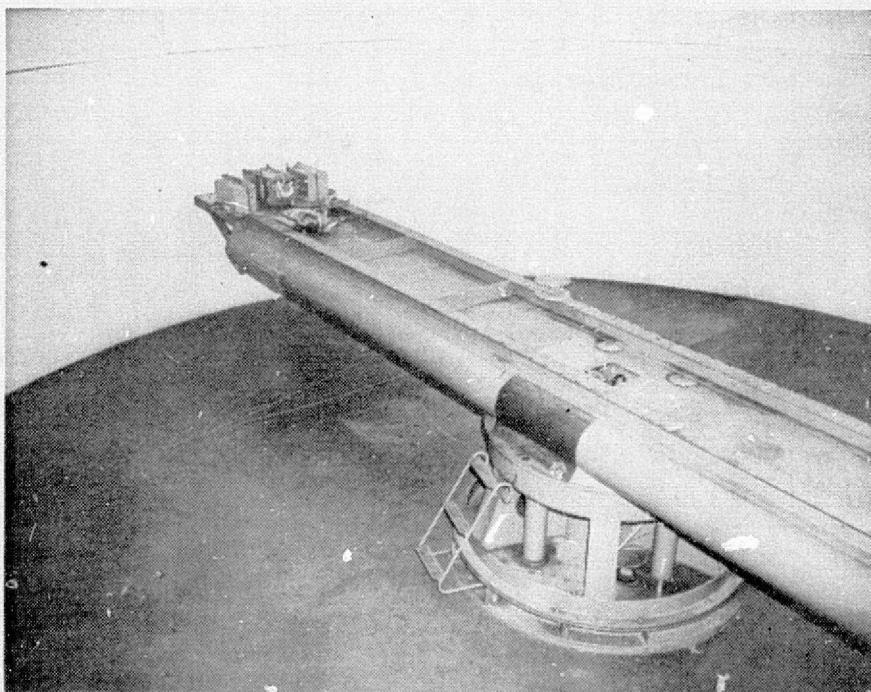
Fluid	Boiling Point (°F)
Acetone	133.2
Ether (diethyl -)	94.3
Pentane	96.8
Trichlorotrifluoroethane	117.6
Chloroform	142.2
Water	212.0
Hexane	154.5
Ethyl Acetate	77.1
Toluene	231.1
Methyl Alcohol	149.0
Benzene	176.2
Heptane	209.1
Carbon Tetrachloride	170.2
Ethyl Alcohol	173.3
Allyl Alcohol	206.6

The centrifuge is powered by a closed-loop hydraulic drive system of 450 horsepower which provides control to within 1/10 rpm. The centrifuge arms, measured from the center of rotation, are of unequal length. Both ends of the centrifuge are commissioned to accept fixtures and instrumentation wiring.

FIGURE 3-10  
CENTRIFUGE MOUNTED 6 IN. DIAMETER TEST TANK



UPRIGHT POSITION PRIOR TO TESTING



TANK MOUNTED IN TESTING POSITION



Various configurations of closed-circuit television are available for test monitoring. Operational capabilities of the centrifuge are listed below:

Manufacturer Model	Rucker 58-3189
Rated capacity	76,000 lb
Maximum accelerations	150 g's
Maximum specimen weight	300 lb
Pit diameter	41 ft
Long-arm radius	15 ft, 10 in.
Short-arm radius	11 ft, 4 in. (18 ft with work platform extension)
Height of arm centerline above floor	4 ft, 4 in.
Slip rings (175) Power	4 at 200 amps 9 at 20 amps
Instrumentation	16 at 6 amps 146 at 2 amps
RF	1 coaxial connector
Universal joints	5,000 psi (2 systems)
hydraulic or	2,500 psi (2 systems)
pneumatic	

## Section 4

### TEST PROCEDURE

#### 4.1 INTRODUCTION

The experimental procedure for the stratification experiments consisted of three major steps:

1. Conditioning the tank, liquid, and vapor.
2. Thermal stratification test.
3. Destratification test.

The conditioning procedure included the steps necessary to reach the saturation condition for the Freon 113 and its vapor at atmospheric pressure. In addition, it was necessary to ensure that any liquid motion produced by the mixer was damped out prior to the initiation of the stratification test period. The thermal stratification period was established by practical limits on the maximum allowable tank pressure and the maximum allowable temperature of the electric wall heaters. This period also had a lower bound associated with the time to reach a quasi-steady-state temperature profile. The destratification period was established from earlier destratification studies (Ref 5). These results were used to define the destratification test period for this program. Details for performing these major steps are included in this section.

#### 4.2 LIQUID, VAPOR, AND TANK CONDITIONING

Conditioning of the Freon 113 prior to the start of a stratification test was necessary to meet the following conditions:

- A. An isothermal system at the Freon 113 saturation state (i. e., at one atmosphere).
- B. The liquid and vapor must be quiescent.

The system was brought to the saturation state with the aid of the wall heaters. The tank vent valve was kept open so that the Freon reached the saturation temperature at one atmosphere. The destratification mixer was

left on during this heating period to aid in maintaining the tank walls and liquid at a uniform temperature. At this point, liquid motion due to the mixer and convection was present. This residual motion was then allowed to decay prior to initiating the stratification tests.

The required decay period was determined in an approximate fashion by operating the destratification pump in the 12 inch tank with the upper dome removed. The pump was turned off and the time required for the visually detectable residual motion to cease was noted. This time was of the order of two minutes and this value was used as a rough guide for the delay period prior to the initiation of a stratification test.

The same steps were taken during the centrifuge experiments. Here, the conditioning operations were conducted with the tank in the vertical position. This was necessary for normal heating and venting, where just before the centrifuge was put in motion the test container was positioned on its side so that its axis remained parallel to the resultant gravity vector of the designated "g" level.

#### 4.3 STRATIFICATION TEST PERIOD

Several criteria were considered when determining the thermal stratification period,  $\theta$ . One criterion was the time required to reach a quasi-steady-state temperature profile in the liquid. The other stratification test period estimate was the time required for the mean temperature of the heated liquid to rise  $15^{\circ}\text{F}$ .

Chin et al (Ref 7), Neff (Ref 8), Schwartz and Holmes (Ref 9), and Tellep and Harper (Ref 10) have all reported that stratification profiles appear to maintain the same shape after an initial transient period. As a consequence, when a quasi-steady-state condition is reached, the propellant tank should act as a lumped-mass system and, the pressure rise rate can be reliably predicted. The time period using this criterion was obtained from a semi-empirical equation obtained by Holmes (Ref 6) using Freon 113. Although the tank used by Holmes did not have the same geometry as the tanks in this study, his equation was selected for comparison with the  $15^{\circ}\text{F}$  temperature rise criterion

as a first approximation. Holmes (Ref 6) obtained the following correlations to fit his data:

$$Fo \cdot Ra_Y^*^{1/5} = 0.2 \frac{D}{Y} \text{ (laminar)} \quad (4-1)$$

and

$$Fo \cdot Ra_Y^*^{2/7} = 1.86 \frac{D}{Y} \text{ (turbulent)} \quad (4-2)$$

The values of  $Gr_H^*$  in this study ranged from  $10^{14}$  to  $10^{16}$  which is generally considered turbulent. However, the lower portion of the tank walls will still be laminar. Therefore, to establish the longest test time required with this criterion the laminar equation was used. The overall system balance was obtained by equating the heat added to the liquid over the stratification test period to the sensible heat gain of the bulk liquid. Here

$$q'' A_T \theta = Q = m_l c_{p_l} (T_{b_f} - T_{b_i}) \quad (4-3)$$

where  $T_{b_f} - T_{b_i} = 15^\circ F$  and  $A_T$  is the wetted area of the tank. It was found that the values of  $\theta$  obtained from equation (4-1) were nearly the same as those obtained using the  $15^\circ F$  mean temperature rise requirement. As a result, the  $15^\circ F$  rise criterion was used to determine  $\theta$ .

#### 4.4 DESTRA TIFICATION TEST PERIOD

The destratification test period was initiated by actuating the simulated jet mixer. Since it was of interest to operate the mixer with and without the wall heaters on, both configurations were considered for some of the experiments. When the wall heaters were left on, the mixer had to overcome the free convection currents in addition to the buoyancy of the stratified fluid.

The thermal destratification results of Poth (Ref 3), without wall heaters operating, clearly indicate that axial jets are superior to radial jets; therefore, only axial jets were used in this study. The results of Poth have also been used to define the minimum destratification time for the unheated cases.

The upper bound of data presented by Poth recommends the following conservative estimate of the mixing time period:

$$\theta_M = 38.25 \frac{D^2}{V_j D_j} \quad (4-4)$$

where

$\theta_M$  = Mixing time

$D$  = Tank diameter

$V_j$  = Jet velocity

$D_j$  = Jet diameter

It should be noted that the predicted values were only considered as a guide since monitoring of the temperature data during the testing provided the most reliable assessment of when the destratification period should be terminated. The time required for mixing with the heaters in operation was not determined prior to the test. Hence, the mixer was kept in operation until the temperatures in the liquid and the tank pressure indicated that mixing had been achieved or until such time that it became apparent that the jet mixer would not overcome the prevailing convective fluid currents.

An analysis was conducted to provide a reasonable upper limit on the jet Reynolds number. A critical jet Reynolds number was defined as that value where the buoyant force becomes unimportant when compared to the inertial forces. For a Reynolds number greater than this critical value, the system may be assumed to mix completely and increasing the jet Reynolds number further simply decreases the mixing time required. Below this critical Reynolds number, the buoyant forces may be strong enough to limit the degree of mixing.

Although a number of analyses were performed to determine this critical Reynolds number, the maximum value is given by

$$Re_j^2 = 0.912 \left( \frac{D}{H} \right)^{2/3} Pr^{-2/3} Gr^{*2/3} \quad (4-5)$$

where

$$Re_j = u_j d / \nu_l ,$$

$u_j$  = Jet velocity at orifice, and

$d$  = Orifice diameter.

This criterion was established by assuming that the mixing jet must possess enough energy at the free surface to overcome the buoyant force, and move the hot liquid at the surface to the bottom of the tank. Using this jet Reynolds number as the critical value, the mixing jet should easily penetrate the stratified layer where the momentum due to the pump is always greater than the free convection momentum, and the liquid kinetic energy due to the pump is always greater than the free convection kinetic energy.

This latter equation was only used as a guide to place a reasonable upper limit on the jet Reynolds number requirements for this study. Observations of the temperature data during destratification also were used to ensure that the critical number was reached.

## Section 5

### EXPERIMENTAL PROGRAM DEFINITION AND TEST MATRIX

#### 5.1 STRATIFICATION

The test matrix presented in this section was defined to check the validity of the dimensionless parameters chosen in Subsection 2.5. Here, scaled pairs of experiments were selected for various combinations of the three different sized tanks. These pairs were arranged to give the widest possible range of values for the dimensionless numbers. Thus, if the dimensionless pressure and temperature values for each scaled pair of tests match each other then these dimensionless groups would be adequate to scale the stratification process. Limitations on the range of values for the dimensionless groups are discussed below.

The first step in defining the bounds on the experimental program was to limit it to that of a single component, Freon 113, and its vapor. Three scaling parameters, the Modified Grashof number ( $Gr^*$ ), the Fourier number ( $Fo$ ), and the Interface number ( $I$ ), were kept constant for the tests which were scaled one to another. Scaling tests were conducted between the 6 inch diameter tank and either the 12 inch or 18 inch diameter tanks. The experiments selected are listed in Table 5-1. All experiments were conducted with liquid heating and some with simultaneous ullage and liquid heating. The test matrix was designed to cover a range of Modified Grashof numbers from  $10^{14}$  to  $10^{16}$ . These limits were established by the allowable heating rates. The upper limit on  $Gr^*$  was set by one of the assumptions made in the dimensional analysis. This was necessary since the governing equations did not include the effects of nucleate boiling on the tank walls. High heat-flux values in the vigorous nucleate boiling range could invalidate the descriptive equations and the resulting dimensionless parameters. For heat flux values in excess of  $1,000 \text{ Btu/hr-ft}^2$ , boiling is expected at atmospheric pressure. As pressurization occurs, boiling should be somewhat depressed;

Table 5-1  
TEST MATRIX - FREON 113 (PCA)

Test Column #1		Test Column #2	Test Column #3
6 in. Dia Tank		12 in. Dia Tank	18 in. Dia Tank
8G	Acceleration - 27G	1G	1G
1,000 Btu/hr ft <sup>2</sup> (L) 87.5% FILL Gr* = 10 <sup>15</sup> TESTS #2, #12S		500 Btu/hr ft <sup>2</sup> (L) 87.5% FILL Gr* = 10 <sup>15</sup> TESTS #30, #25	
1,000 Btu/hr ft <sup>2</sup> (L+U) 87.5% FILL Gr* = 10 <sup>15</sup> TESTS #3, #11S		500 Btu/hr ft <sup>2</sup> (L+U) 87.5% FILL Gr* = 10 <sup>15</sup> TESTS #31, #17	
700 Btu/hr ft <sup>2</sup> (L) 50% FILL Gr* = 10 <sup>14</sup> TESTS #95, #15S		350 Btu/hr ft <sup>2</sup> (L) 50% FILL Gr* = 10 <sup>14</sup> TESTS #33, #32	
700 Btu/hr ft <sup>2</sup> (L+U) 50% FILL Gr* = 10 <sup>14</sup> TESTS #10S, #16S		350 Btu/hr ft <sup>2</sup> (L+U) 50% FILL Gr* = 10 <sup>14</sup> TESTS #34, #35	
600 Btu/hr ft <sup>2</sup> (L) 87.5% FILL Gr* = 7 x 10 <sup>14</sup> TESTS #1, #5, #8S		300 Btu/hr ft <sup>2</sup> (L) 87.5% FILL Gr* = 7 x 10 <sup>14</sup> TESTS #20, #22	
600 Btu/hr ft <sup>2</sup> (L+U) 87.5% FILL Gr* = 7 x 10 <sup>14</sup> TESTS #4, #6		300 Btu/hr ft <sup>2</sup> (L+U) 87.5% FILL Gr* = 7 x 10 <sup>14</sup> TESTS #23, #28	
90 Btu/hr ft <sup>2</sup> (L) 87.5% FILL Gr* = 10 <sup>14</sup> TEST #14		45 Btu/hr ft <sup>2</sup> (L) 87.5% FILL Gr* = 10 <sup>14</sup> TESTS #26, #15	
90 Btu/hr ft <sup>2</sup> (L+U) 87.5% FILL Gr* = 10 <sup>14</sup> TEST #13		45 Btu/hr ft <sup>2</sup> (L+U) 87.5% FILL Gr* = 10 <sup>14</sup> TEST #27	
	2,230 Btu/hr ft <sup>2</sup> (L) 50% FILL Gr* = 10 <sup>15</sup> TEST #1S		748 Btu/hr ft <sup>2</sup> (L) 50% FILL Gr* = 10 <sup>15</sup> TESTS #BS, #D
	2,880 Btu/hr ft <sup>2</sup> (L) 87.5% FILL Gr* = 10 <sup>16</sup> TEST #3S		960 Btu/hr ft <sup>2</sup> (L) 87.5% FILL Gr* = 10 <sup>16</sup> TEST #1S

NOTES:

- (L), (L+U) ... Liquid, and Liquid + Ullage Heating.
- Tests horizontally across Table are scaling tests (i.e., tests having constant Modified Grashof no.  $Gr^* = Gr_H^* = f(L = \text{liquid depth})$ ).
- "S" ... S in tests number indicates no heating during destratification testing.



however, a quantitative assessment of this effect is not known. Nevertheless, several experiments were conducted at heat-flux values near  $3,000 \text{ Btu/hr-ft}^2$ .

This value of heat flux was selected as a conservative upper limit for protecting the heater blankets. Therefore, it was not anticipated that the effect of boiling on scaling would be specifically determined other than by looking for changes in the pressure rise rate and the stratification profiles in the higher heat-flux range. The lower bound on  $Gr^*$ , or in effect  $q''$ , was the degree to which the tank insulation acts as an adiabatic wall. Rough estimates on the heat leak through the insulation with the 12 inch tank were made from preliminary data and indicated that this value was between 1 and  $10 \text{ Btu/hr-ft}^2$ . Thus,  $45 \text{ Btu/hr-ft}^2$  was arbitrarily selected as the lower limit on  $q''$ . This condition corresponded to a Modified Grashof number of  $10^{14}$  and it was the lowest value studied.

Specific values of the Fourier number would not be an important consideration other than it be in keeping with expected values for space vehicles. Thus, to check scaling, a convenient value of the Fourier number was selected. Here, the stratification period  $\theta$  was selected to obtain an increase in the liquid temperature of the order of  $15^\circ\text{F}$  which also corresponded to a pressure rise in the tank of the order of 5 psig. Smaller values could result in serious experimental error since temperature increases should be approximately an order of magnitude greater than the thermocouple error and larger values could tend to reach the safety limits of the tanks. The third dimensionless parameter did not include any new terms associated with the tank and thus did not impose any further limits on the experimental range of variables. The fraction of the tank volume occupied by the liquid in this study had two values, 50 percent and 87.5 percent. Scaling between two tanks required that the percent fill be the same.

## 5.2 DESTRA TIFICATION

Although the scaling procedure did not specifically include the destratification process, there is reason to believe that scaling during this period should require the same dimensionless numbers as used in the stratification period along with the Reynolds number. As a result, the jet Reynolds number was

treated as an additional pi-group during this period. Table 5-2 lists these jet Reynolds numbers; and, it should be noted that all scaled tests were not carried over in the destratification test region.

Table 5-2

TEST MATRIX - DESTRATIFICATION JET REYNOLDS NUMBERS

Test Column #1 6 in. Dia Tank 8G - Acceleration - 27G		Test Column #2 12 in. Dia Tank 1G	Test Column #3 18 in. Dia Tank 1G
Tests #2, #12S $Re_j = 38K, 38K$		Tests #30, #25 $Re_j = 38K, 31K$	
Tests #3, #11S $Re_j = 38K, 38K$		Tests #31, #17 $Re_j = 38K, 31K$	
Tests #9S, #15S $Re_j = 38K, 38K$		Tests #33, #32 $Re_j = 31K, 24K$	
Tests #10S, 16S $Re_j = 38K, 45.1K$		Tests #34, #35 $Re_j = 31K, 20K$	
Tests #1, #8S, #5 $Re_j = 31K, 38K, 31K$		Tests #20, #22 $Re_j = 31K, 31K$	
Tests #4, #6 $Re_j = 31K, 31K$		Tests #23, #28 $Re_j = 31K, 31K$	
Test #14 $Re_j = 38K$		Tests #26, #15 $Re_j = 31K, 25K$	
Test #13 $Re_j = 38K$		Test #27 $Re_j = 31K$	
	Test #1S $Re_j = 38K$		Test #BS, #D $Re_j = 38K, 38K$
	Test #3S $Re_j = 45.1K$		Test #IS $Re_j = 45.1K$

Note:  $Re_j$  . . . . Reynolds number of destratification (mixing) flow at nozzle exit.

## Section 6

### DISCUSSION AND ANALYSIS OF RESULTS

#### 6.1 INTRODUCTION

The data in this study correspond to those experiments listed in the test matrix (Table 5-1) for the 6, 12, and 18 inch tanks. Reproducibility is the first item covered to establish data reliability. Here, curves are presented for sets of identical experiments to indicate the spread in data due to experimental error. The Modified Grashof number definition was expanded to differentiate between the heat flux produced by the blanket heaters and that which actually enters the tank fluid. Then, the criteria which must be met to obtain scaling are discussed. Finally, Modified Grashof number, Fourier number, Interface number, pressure, and temperature data are presented and examined with these criteria to assess the degree to which scaling was achieved.

The test liquid (Freon 113) properties, characteristic pressure and temperature values, the values of the three scaling parameters; Modified Grashof numbers ( $Gr_H^*$  and  $Gr_l^*$ ), Fourier number ( $Fo$ ), and Interface number ( $I$ ), for each test investigated are included in Appendix A. A summary of the heat absorbed by the liquid, the tank walls and heaters, stratification test time, and the heat source rates are tabulated for each test investigated in Appendix B. These tables show that the heat accounted for through thermocouple measurements for all tests was about 95.5 percent of the heat actually generated by the heater blankets. This provided a measure with which to gage the accuracy of the temperature values in the liquid, the ullage, and the tank.

#### 6.2 DATA REPRODUCIBILITY

##### 6.2.1 Introduction

Data reproducibility was evaluated according to the measured-bulk liquid temperature and tank-pressure percent deviations achieved from repeated

test conditions conducted over a period of time ranging from days to months. Fourteen tests were repeated for reproducibility. The degree of reproducibility is discussed below.

### 6.2.2 Pressure History Curves

The pressure history curves shown in Figures 6-1 through 6-14 correspond to some of the test listed in the test matrix (Table 5-1). These curves show good agreement for all test operating conditions in the Modified Grashof number range of  $10^{14}$  through  $10^{16}$ , for the range of 50 and 87.5 percent liquid fill, and for the liquid, and liquid and ullage heating conditions. It was noted that the initial pressure in some tests were not the same. This is partially due to the variation in the barometric pressure conditions. However, in these test cases with the initial shift in pressure, the reproducible pressure curves have remained essentially parallel. Hence, the same increase in pressure during the repeated tests indicates that the variation of the pressure data from test to test was small.

In addition to the graphical representation, a quantitative assessment of the pressure variations was made by determining the percent deviation of the reproducible pressure data. This was done by determining the pressure increase of each of the respective tests and then dividing it by the averaged initial pressure of each of the two reproducible tests to be compared.

This percent deviation is defined as follows:

$$\frac{\Delta p_{A-B}}{p_{iavg}} = \left| \frac{p_{Af} - p_{Ai}}{1/2 (p_{Ai} + p_{Bi})} - \frac{p_{Bf} - p_{Bi}}{1/2 (p_{Ai} + p_{Bi})} \right| \quad (6-1)$$

The maximum deviation of pressure reproducibility is about 9.8 percent. Table 6-1 gives the values for all of the tests.

Based on the reproducibility of the pressure data curves, Figure 6-1 through 6-14, and the pressure deviation percentages shown in Table 6-1, it is concluded that a high degree of reproducibility was achieved between two or more identical tests. It is noted that these tests were repeated in a random fashion. Tests were repeated from 1 to 30 days after the initial tests were conducted. This further demonstrated not only the reproducibility and

## PRESSURE REPRODUCIBILITY CURVES

FIGURES 6-1 THROUGH 6-14

### NOMENCLATURE

$q_H''$  = Measured heater heat flux input, Btu/hr ft<sup>2</sup>

$Re_j$  = Reynolds number at mixer jet nozzle

FIGURE 6-1  
REPRODUCIBILITY DATA  
6 IN. TANK - PRESS. HISTORY: TESTS 8G NO. 2 AND NO. 12S

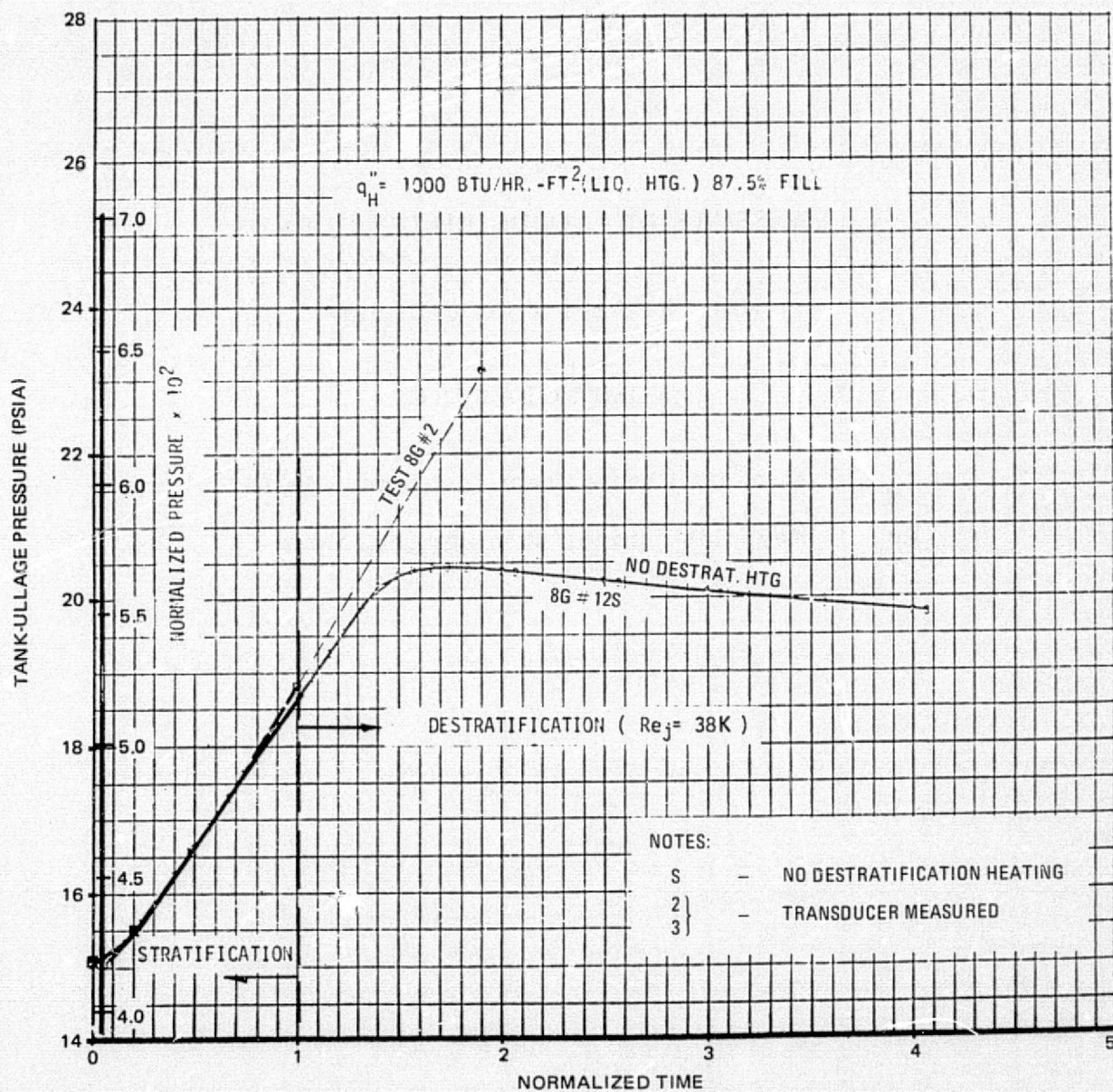




FIGURE 6-2  
REPRODUCIBILITY DATA  
6 IN. TANK-PRESS. HISTORY: TESTS 8G NO. 3 AND NO. 11S

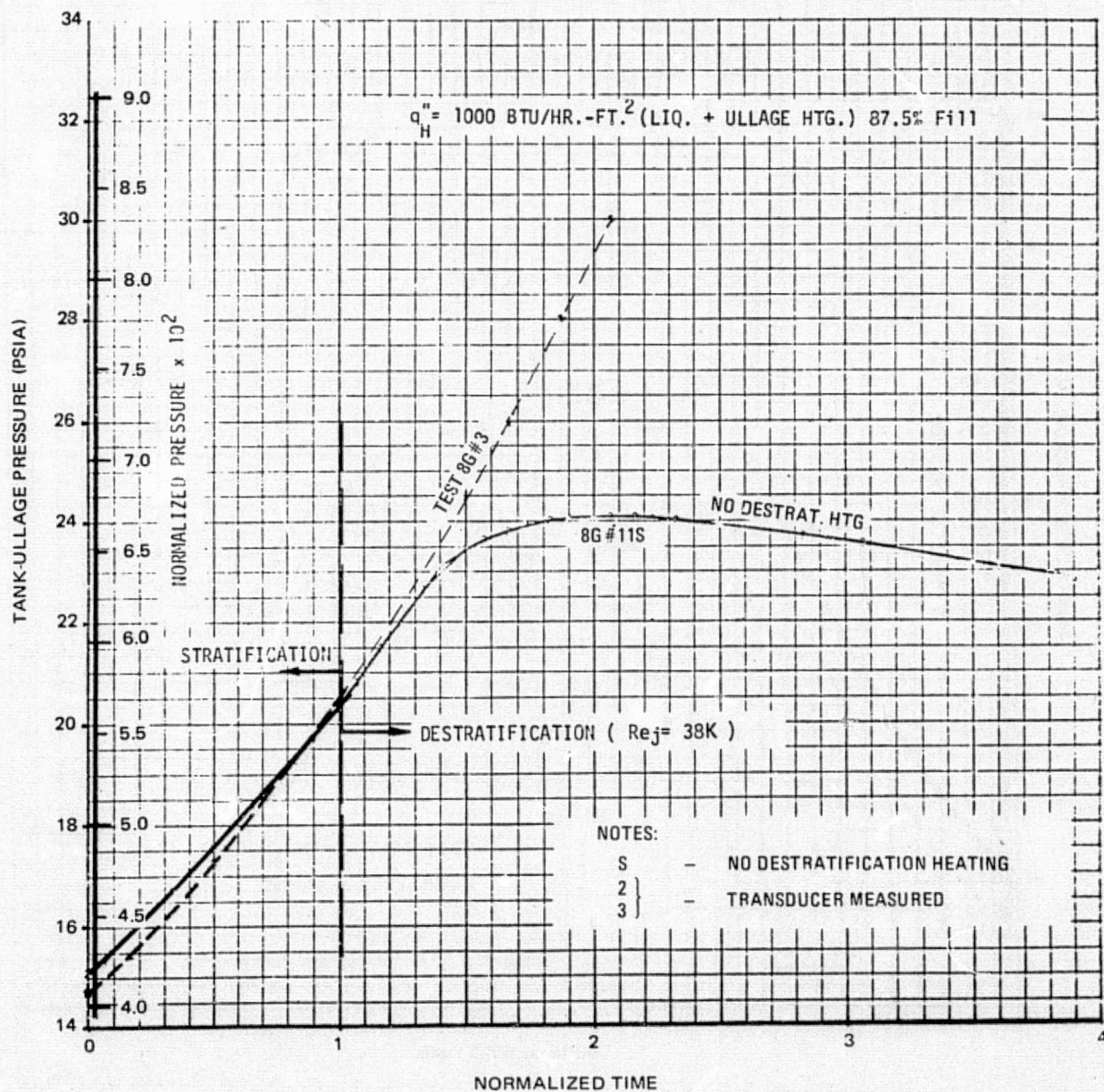


FIGURE 6-3  
REPRODUCIBILITY DATA  
6 IN. TANK-PRESS. HISTORY: TESTS 8G NO. 9S AND NO. 15S

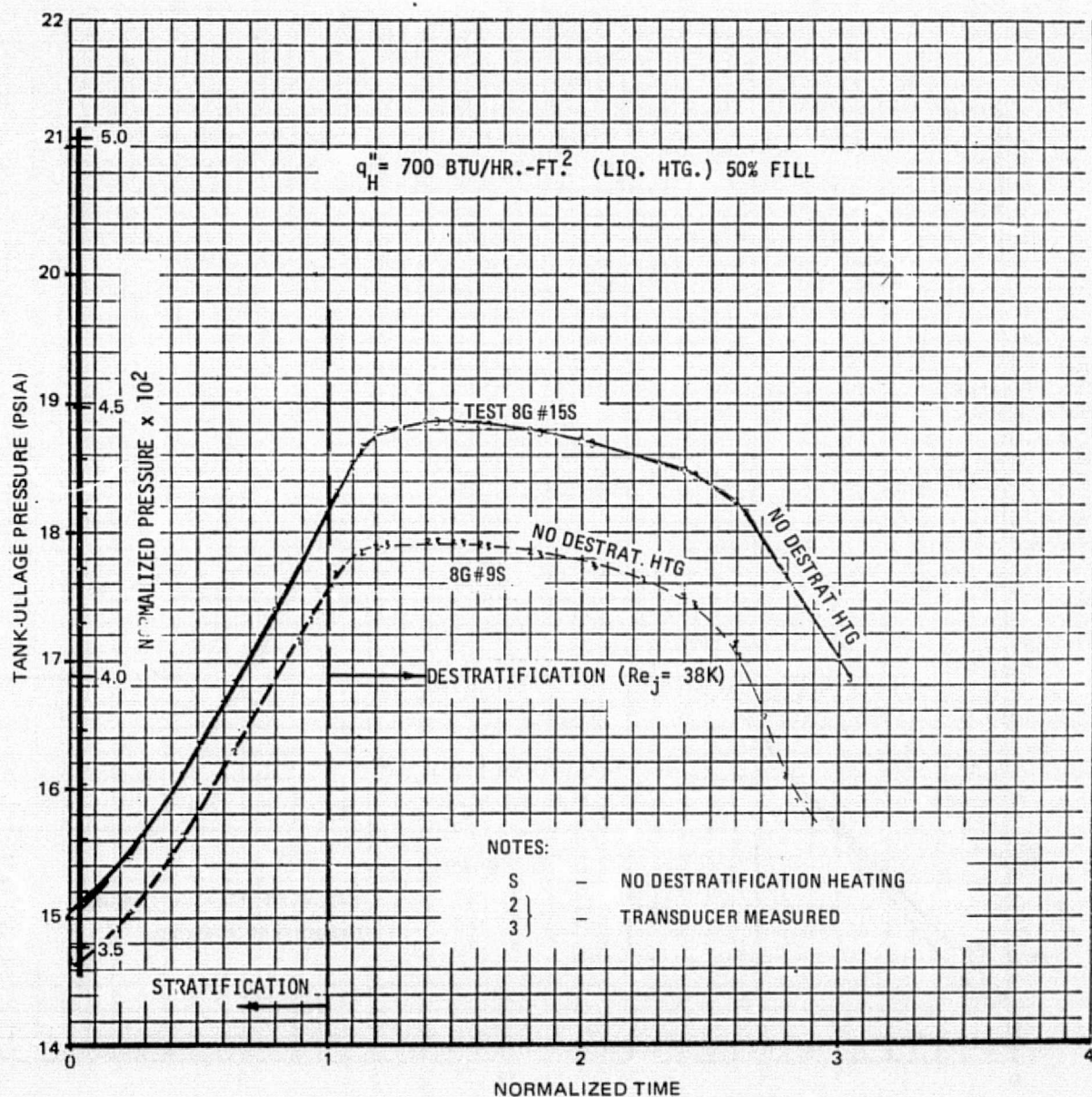




FIGURE 6-4  
REPRODUCIBILITY DATA  
6 IN. TANK-PRESS. HISTORY: TESTS 8G NO. 10 AND NO. 16S

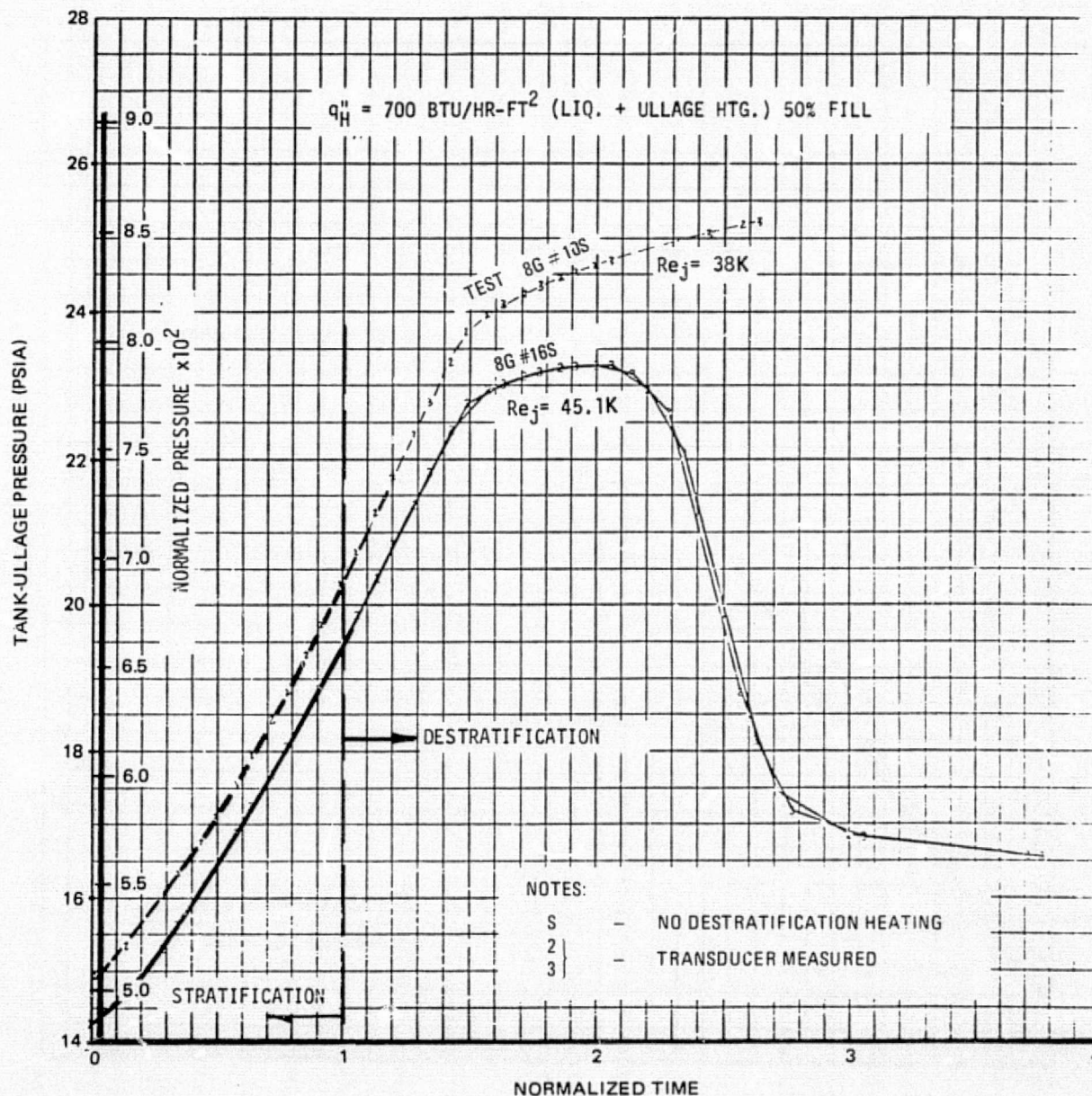


FIGURE 6-5  
REPRODUCIBILITY DATA  
6 IN. TANK-PRESS. HISTORY: TESTS 8G NO. 1, NO. 5, AND NO. 8S

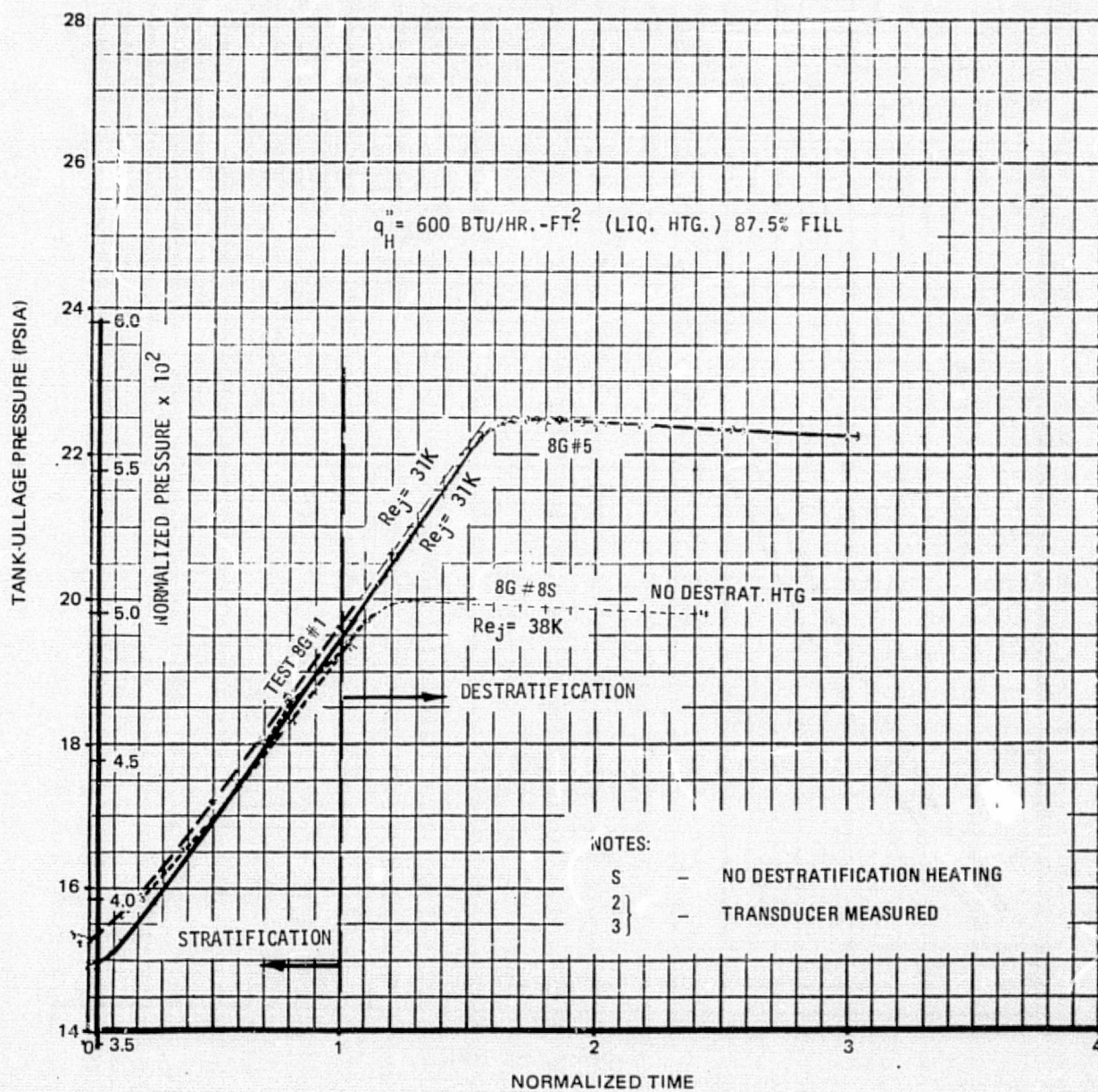




FIGURE 6-6  
REPRODUCIBILITY DATA  
6 IN. TANK-PRESS. HISTORY: TESTS 8G NO. 4 AND NO. 6

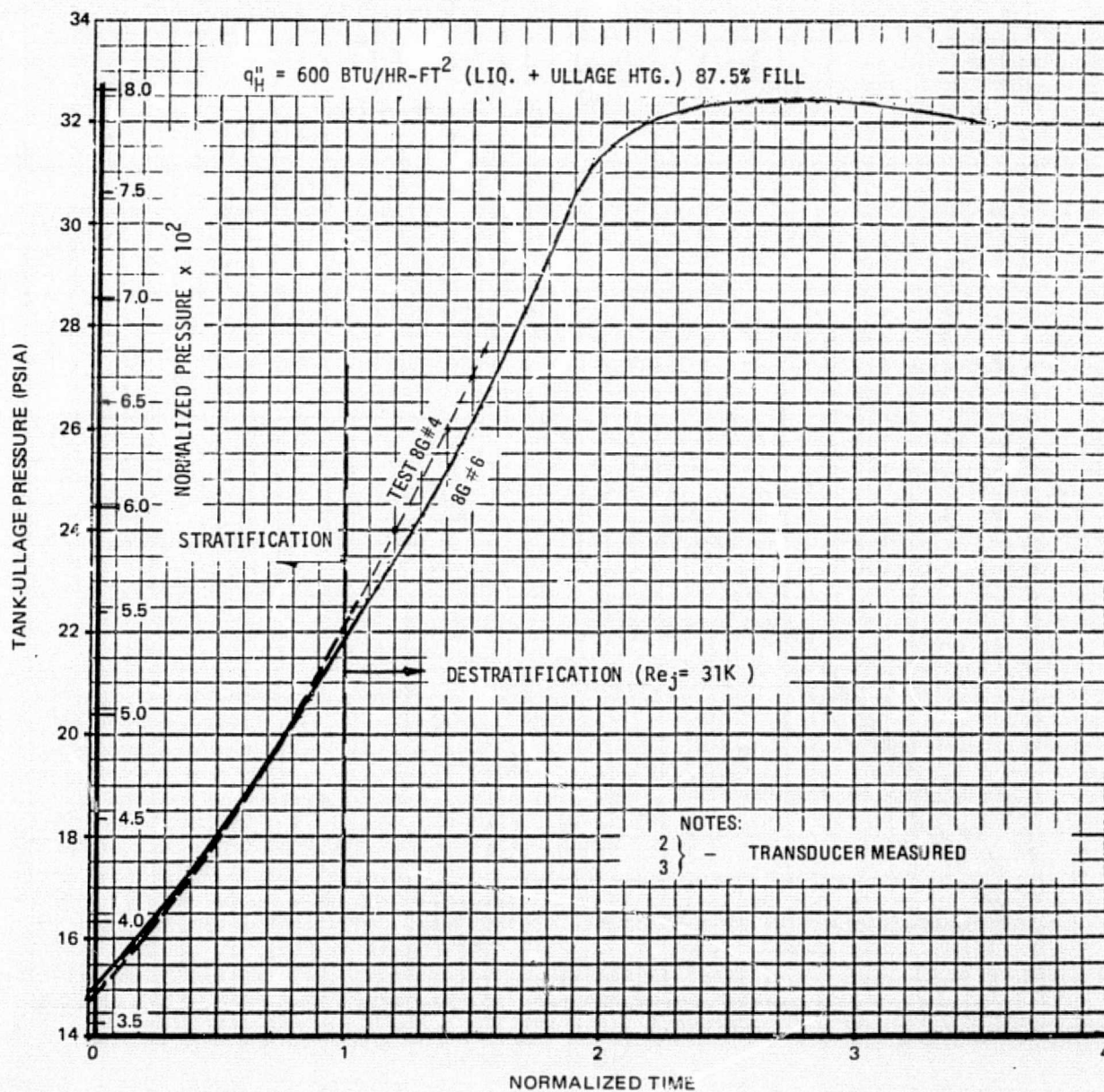


FIGURE 6-7  
REPRODUCIBILITY DATA  
12 IN. TANK-PRESS. HISTORY: TESTS 1G NO. 30 AND NO. 25

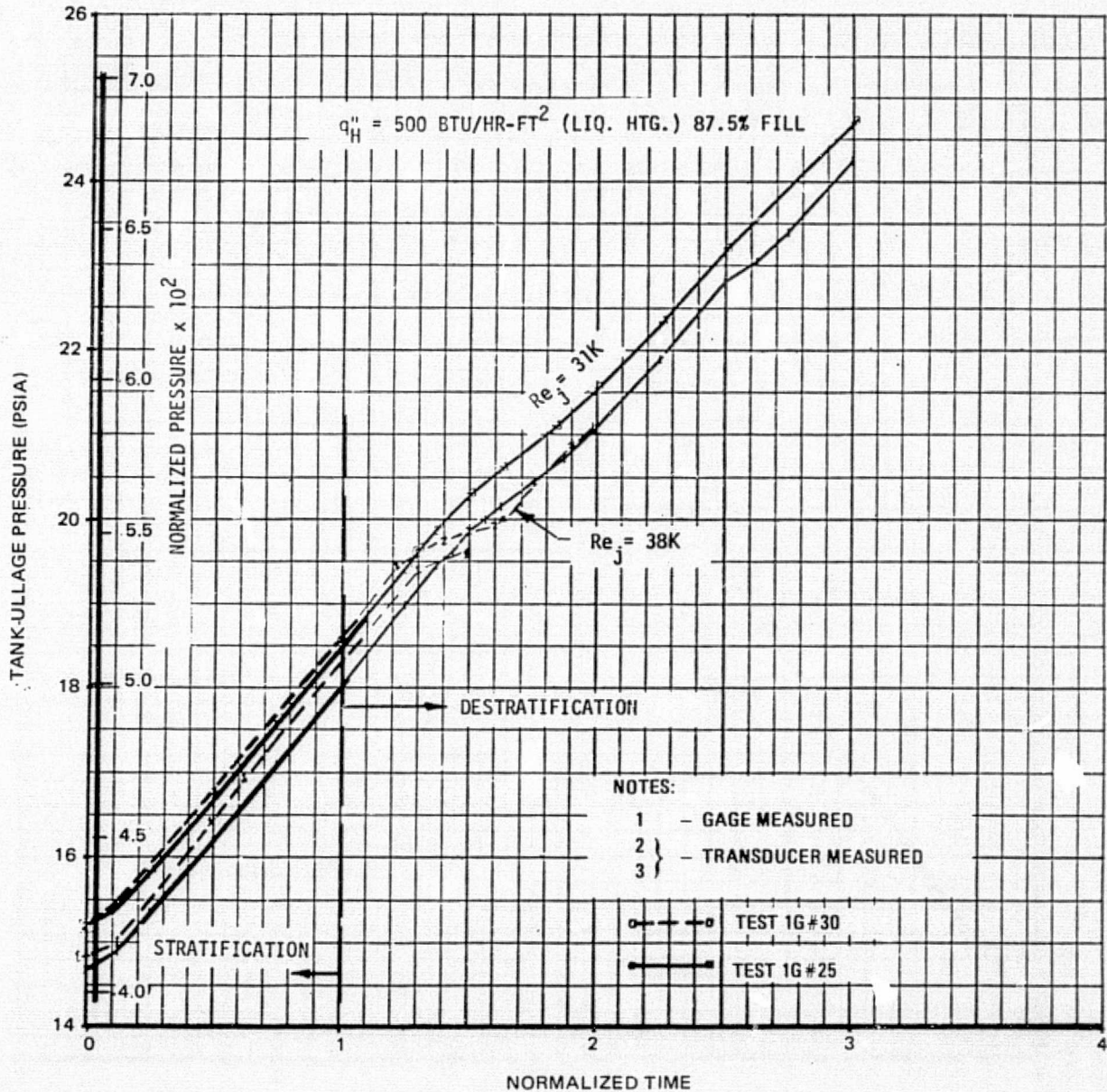




FIGURE 6-8  
REPRODUCIBILITY DATA  
12 IN. TANK-PRESS. HISTORY: TESTS 1G NO. 31 AND NO. 17

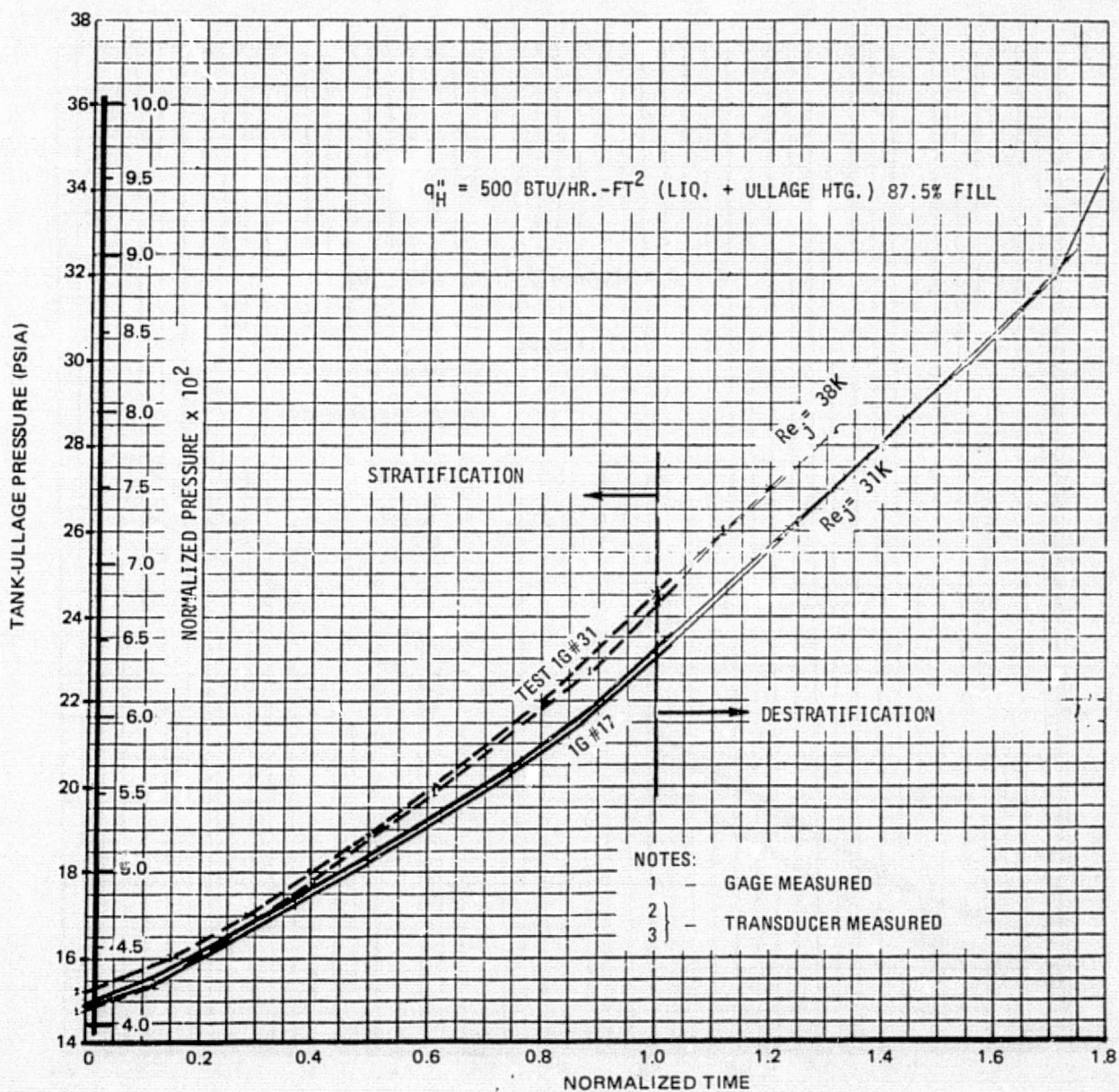


FIGURE 6-9  
REPRODUCIBILITY DATA  
12 IN. TANK-PRESS. HISTORY: TESTS 1G NO. 33 AND NO. 32

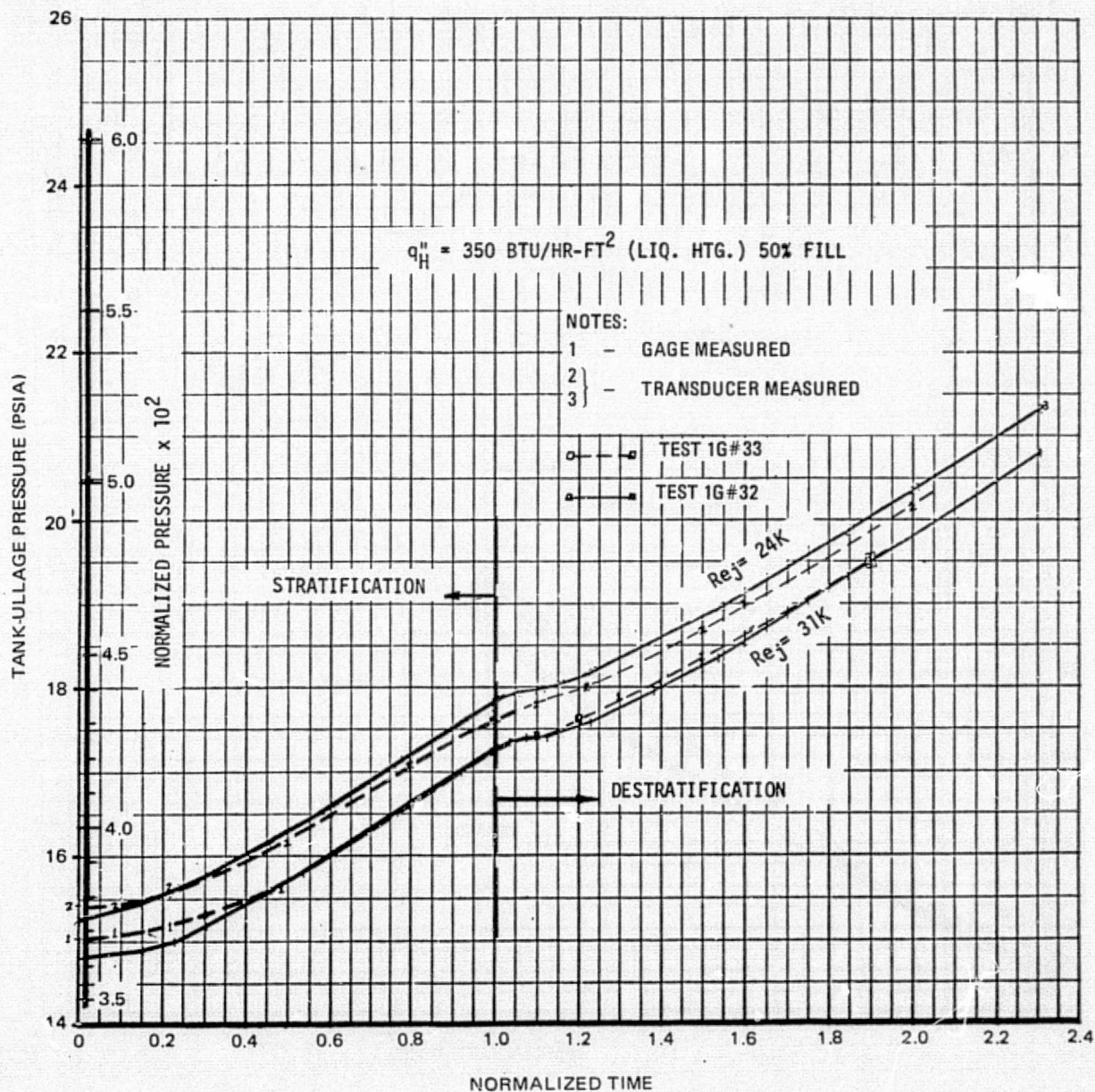




FIGURE 6-10  
REPRODUCIBILITY DATA  
12 IN. TANK-PRESS. HISTORY: TESTS 1G NO. 34 AND NO. 35

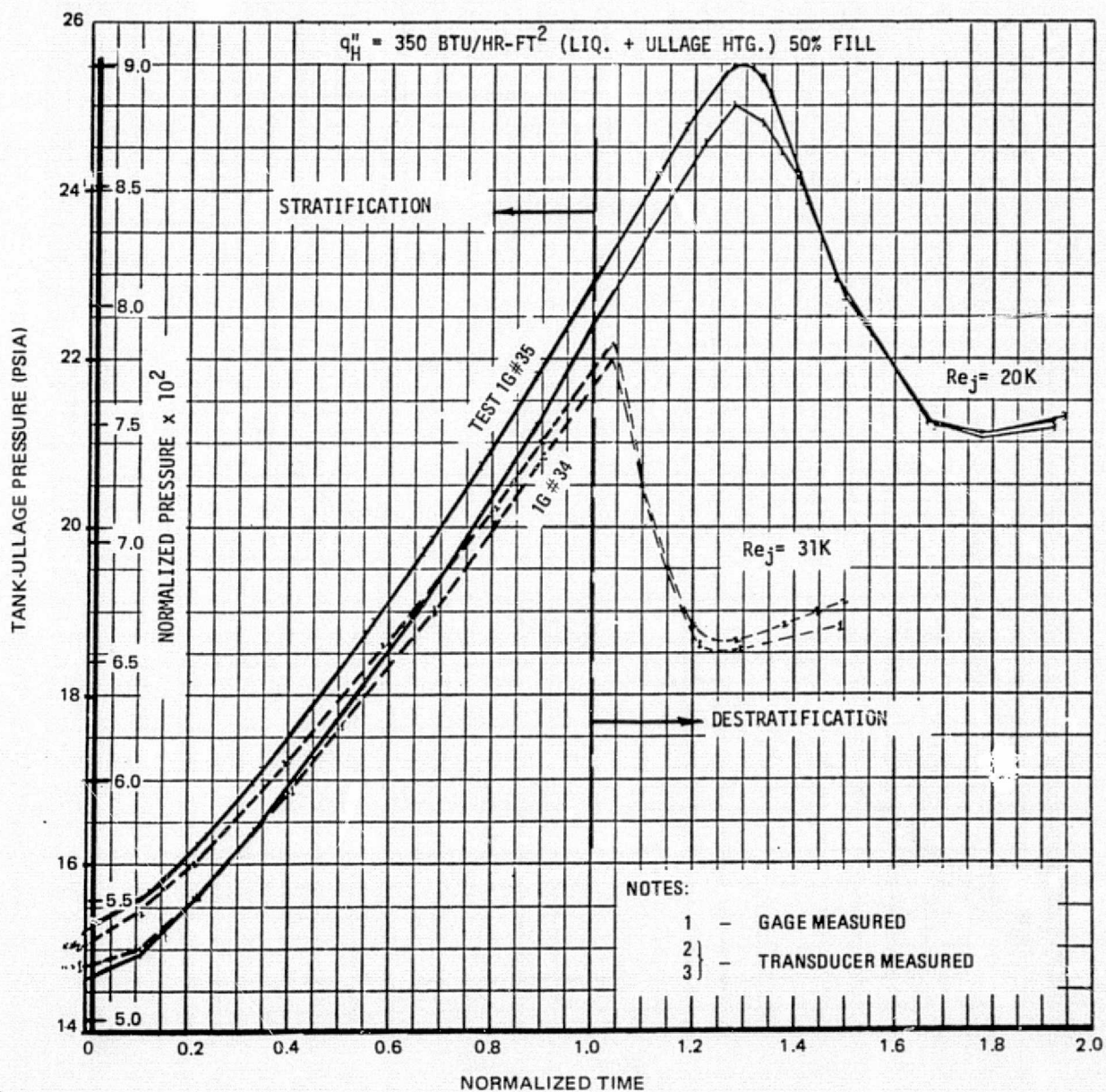


FIGURE 6-11  
REPRODUCIBILITY DATA  
12 IN. TANK-PRESS. HISTORY: TESTS 1G NO. 20 AND NO. 22

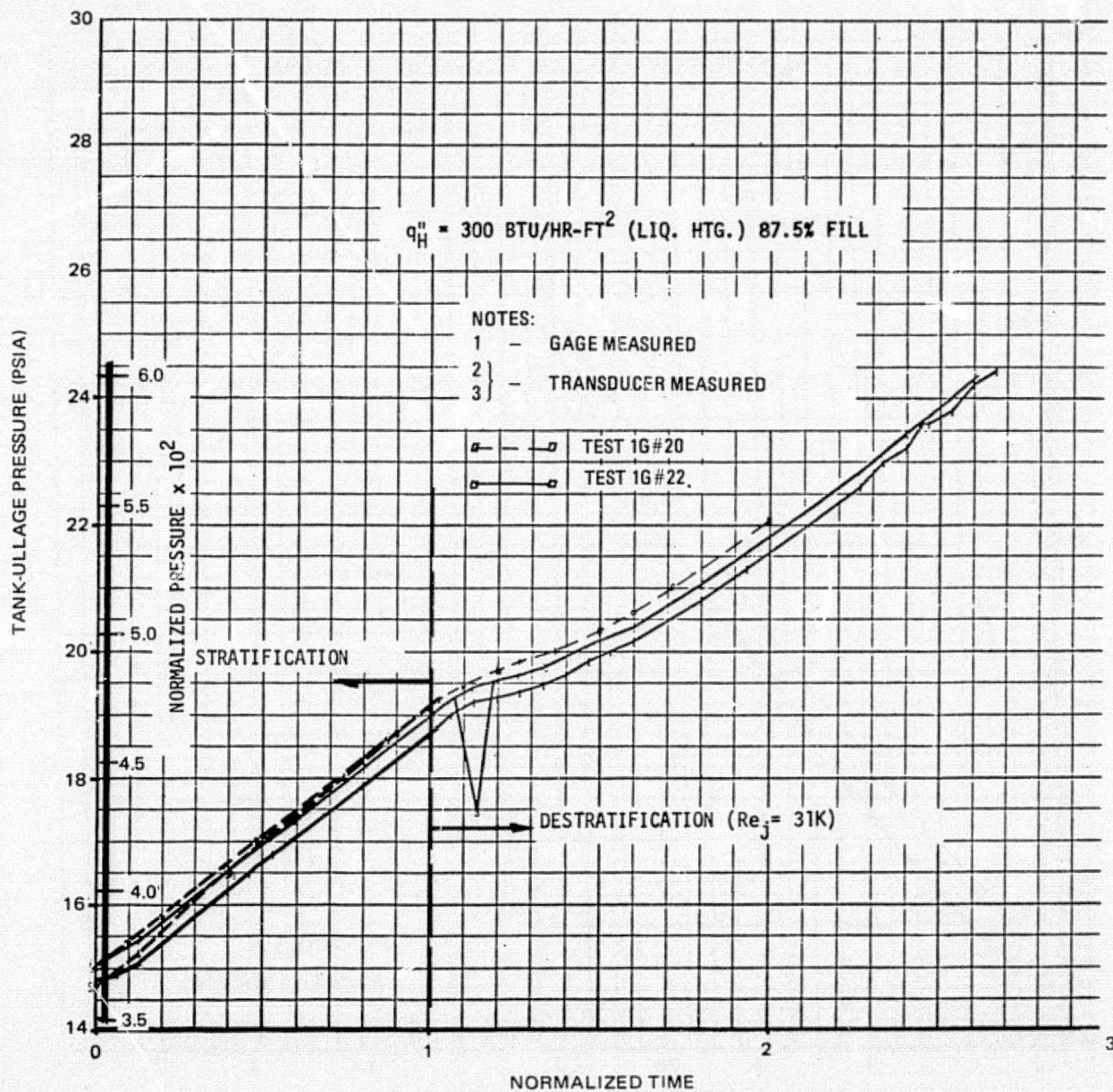




FIGURE 6-12  
REPRODUCIBILITY DATA  
12 IN. TANK-PRESS. HISTORY: TESTS 1G NO. 23 AND NO. 28

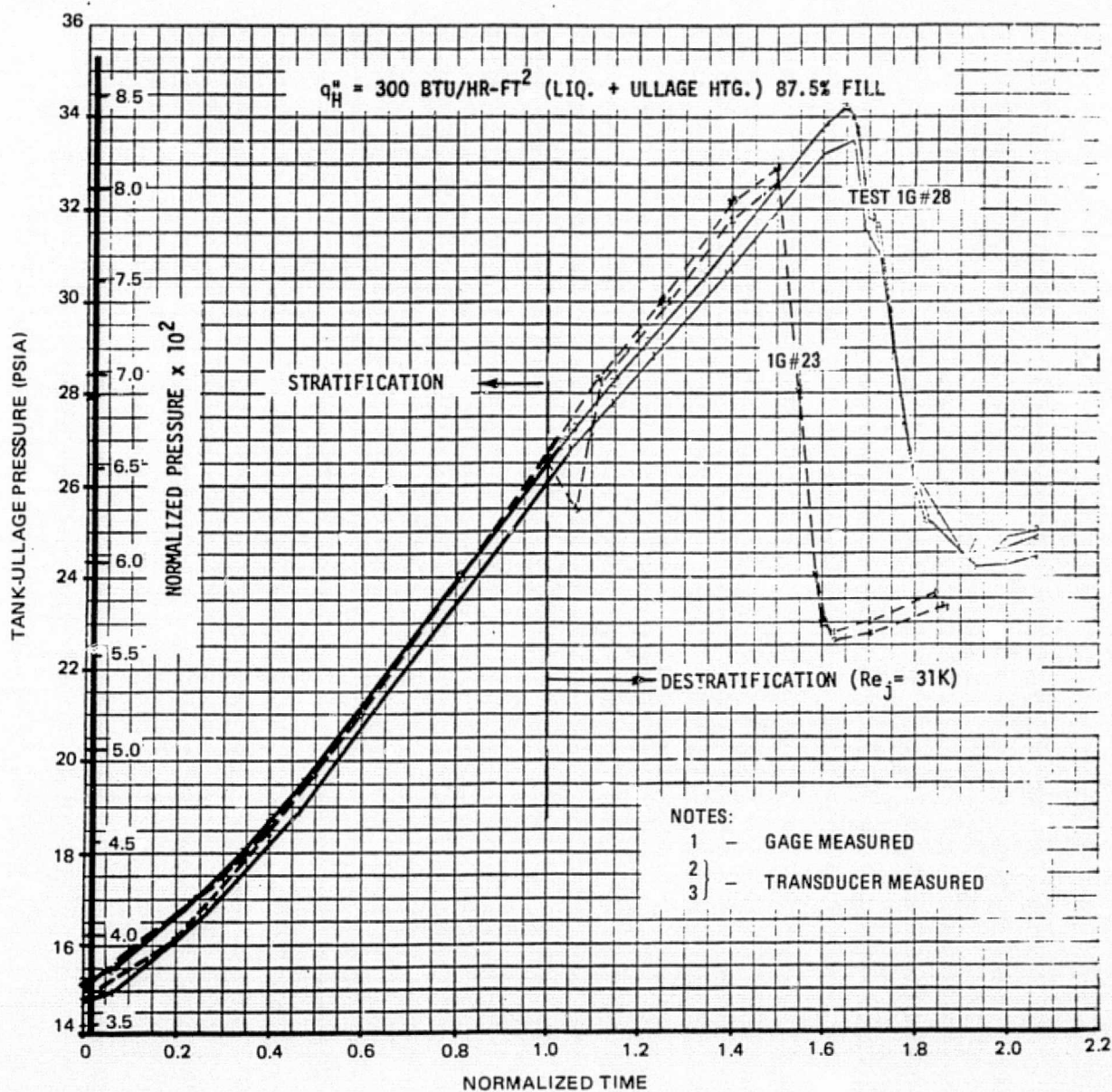


FIGURE 6-13  
REPRODUCIBILITY DATA  
12 IN. TANK-PRESS. HISTORY: TESTS 1G NO. 26 AND NO. 15

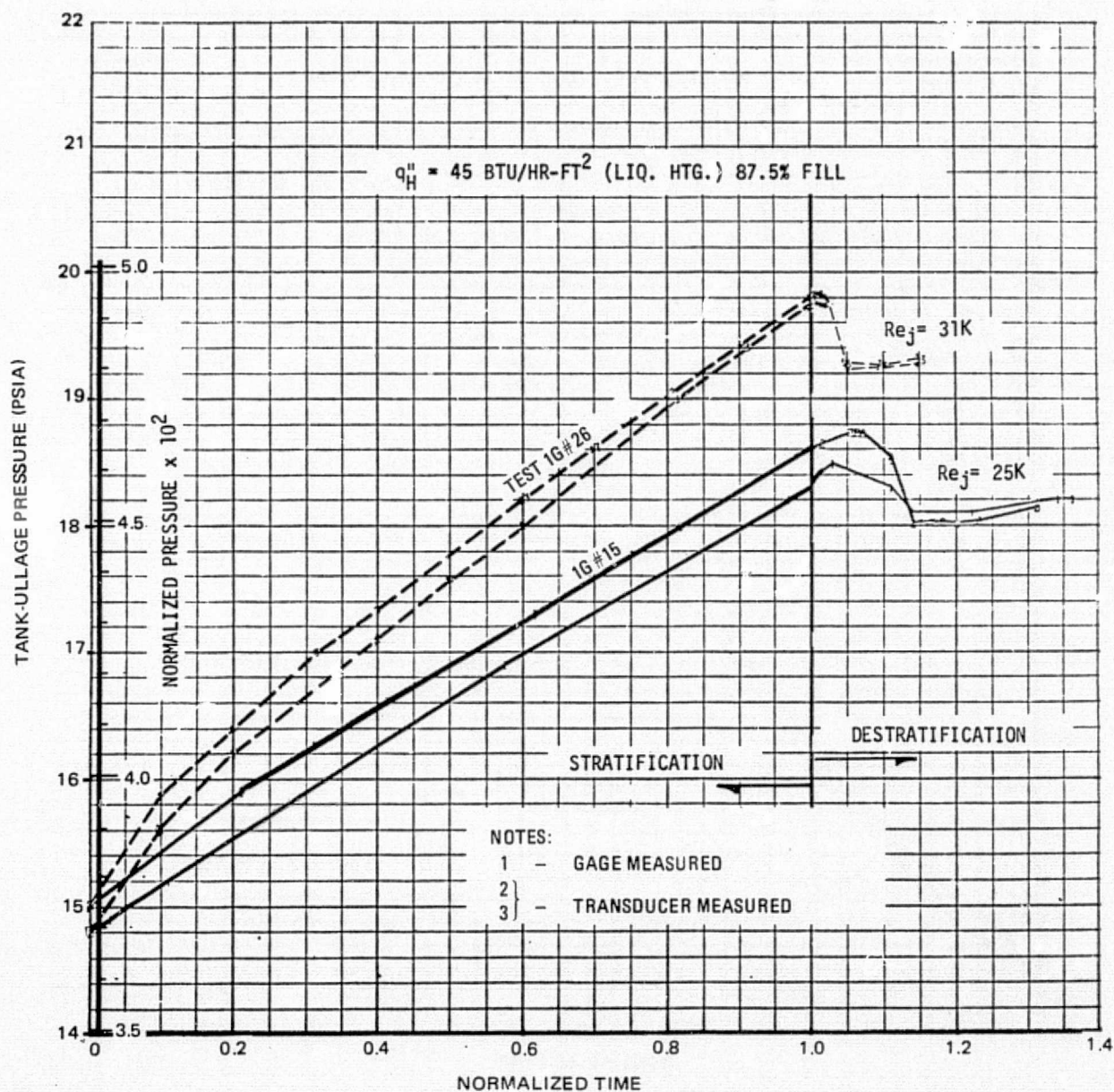


FIGURE 6-14  
REPRODUCIBILITY DATA  
18 IN. TANK-PRESS. HISTORY: TESTS 1G NO. BS AND NO. D

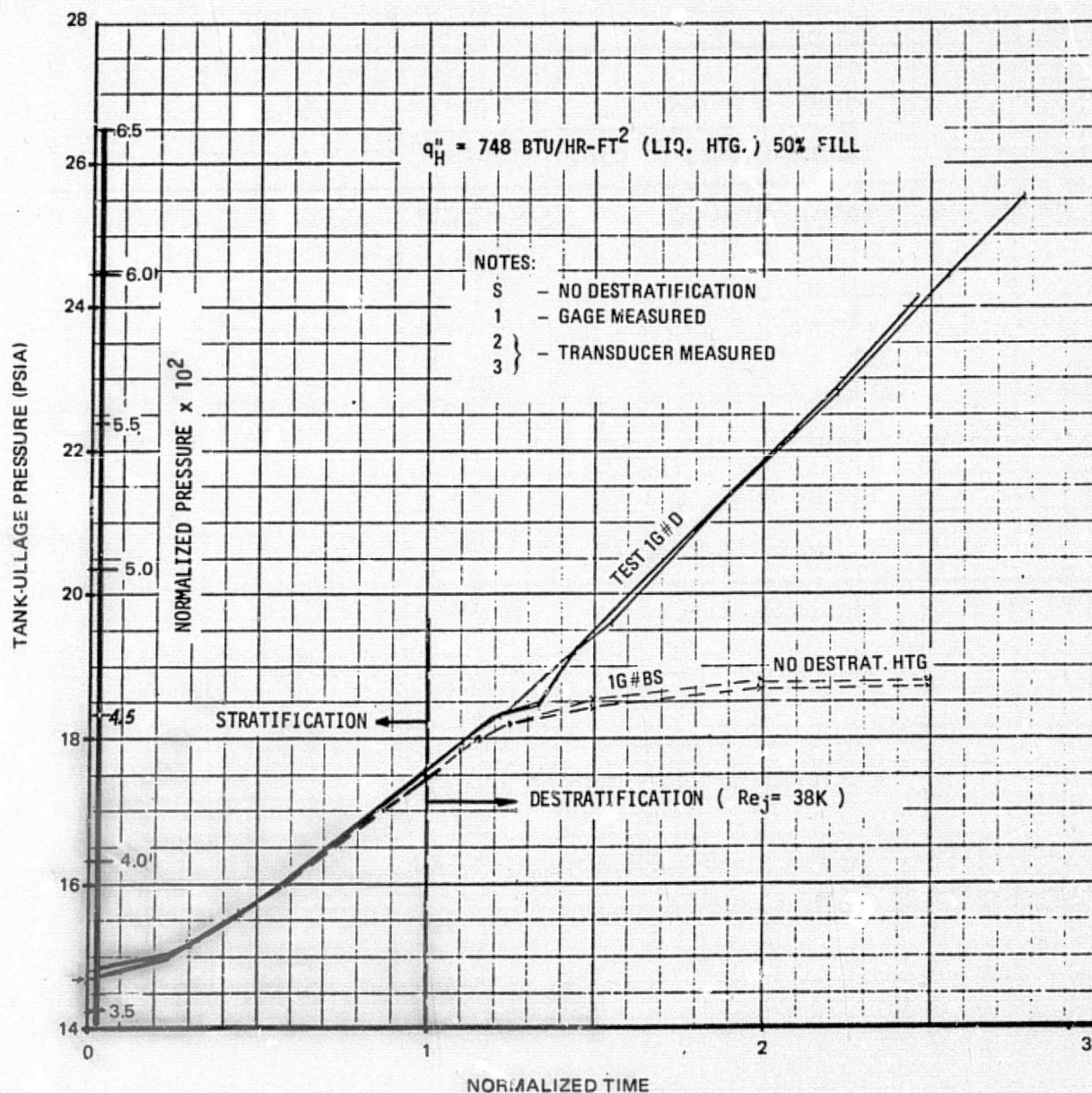




Table 6-1  
PRESSURE DEVIATION (PERCENT)  
(REPRODUCIBILITY)

			$G_H$	Transducer, Pressure (Percent)	Gage Pressure (Percent)
6-Inch-Diameter Tank			$10^{14}$  $10^{14}$  $7 \times 10^{14}$ $10^{15}$  $7 \times 10^{14}$ $10^{15}$	1.7  2.0  3.5 1.0  2.8 4.3	
	50% Fill	Liquid Heating			
		Liquid-Ullage Heating			
	87.5% Fill	Liquid Heating			
		Liquid-Ullage Heating			
12-Inch-Diameter Tank			$10^{14}$  $10^{14}$  $10^{14}$ $7 \times 10^{14}$ $10^{15}$  $7 \times 10^{14}$ $10^{15}$	2.2  6.0  8.0 1.0 0.7  2.4 6.7	1.7  5.4  9.8 3.9 1.3  2.8 8.4
	50% Fill	Liquid Heating			
		Liquid-Ullage Heating			
	87.5% Fill	Liquid Heating			
		Liquid-Ullage Heating			
18-Inch-Diameter Tank					
	50% Fill	Liquid Heating			

reliability but also the consistency of the entire test tank system models and apparatus over the range from 1 to 27 g's.

### 6.2.3 Temperature Profile Curves

The dimensional and dimensionless temperature profile curves at the normalized time ( $\tau$ ) equal to 1.0 are shown in Figures 6-15 through 6-31.

The curves show that there is good reliability in achieving reproducibility of the temperature measurements throughout the fluid. In addition, since the dimensionless temperature ( $\bar{T}$ ) and the dimensional temperature ( $T$ ) only differ by a constant, both scales can be used to represent the same curve on any given graph. An examination of these temperature profiles for identical test conditions shows that the reproducibility tests nearly collapse on top of one another, with little difference in the temperature readings at each thermocouple location. Here, the temperature scatter is less than  $2^{\circ}\text{F}$  at each thermocouple location. The reliability of reproducing test data over an elapsed period of time of 5 and 17 months apart is demonstrated by inspection of the temperature profiles shown in Figures 6-29 through 6-31. These curves show good reproducibility.

The normalized liquid-bulk temperatures (average liquid temperature) shown in Figures 6-32 through 6-45, were also analyzed for determining the percent deviation values (Table 6-2). The method used is identical to that used for determining the percent deviation values for the pressure data discussed in Subsection 6.2.2.

Here, the percent deviation is defined and expressed as

$$\frac{\Delta T_{A-B}}{\Delta T_{i\text{avg}}} = \left| \frac{T_{Af} - T_{Ai}}{1/2 (T_{Ai} + T_{Bi})} - \frac{T_{Bf} - T_{Bi}}{1/2 (T_{Ai} + T_{Bi})} \right| \quad 6-2$$

Note that this technique automatically adjusts the comparison to account for the differences in the starting temperature whereas, Figures 6-32 through 6-45 do not. As a result, when the starting temperatures are different, the curves



## TEMPERATURE PROFILE REPRODUCIBILITY CURVES

FIGURES 6-15 THROUGH 6-31

### NOMENCLATURE

$q_H''$	Measured heater heat-flux input, Btu/hr-ft <sup>2</sup>
"s"	Symbol in test number indicates no destratification heating
(L)	Liquid heating only
(L+U)	Liquid and ullage heating
Liquid	Freon 113 (PCA)
$\tau$	$\tau = (t/\theta)$ where $\tau$ = Normalized time $t$ = Elapsed time test $\theta$ = Stratification test time
6-In. Tank.	Title refers to tank diameter
$Gr_H^*$	Modified Grashof number based upon $q_H''$

FIGURE 6-15  
 REPRODUCIBILITY DATA  
 6 IN. TANK - STRAT TEMP PROFILES ( $\tau = 1.0$ )  
 TESTS 8G NO. 2 AND NO. 12S (L) HEATING

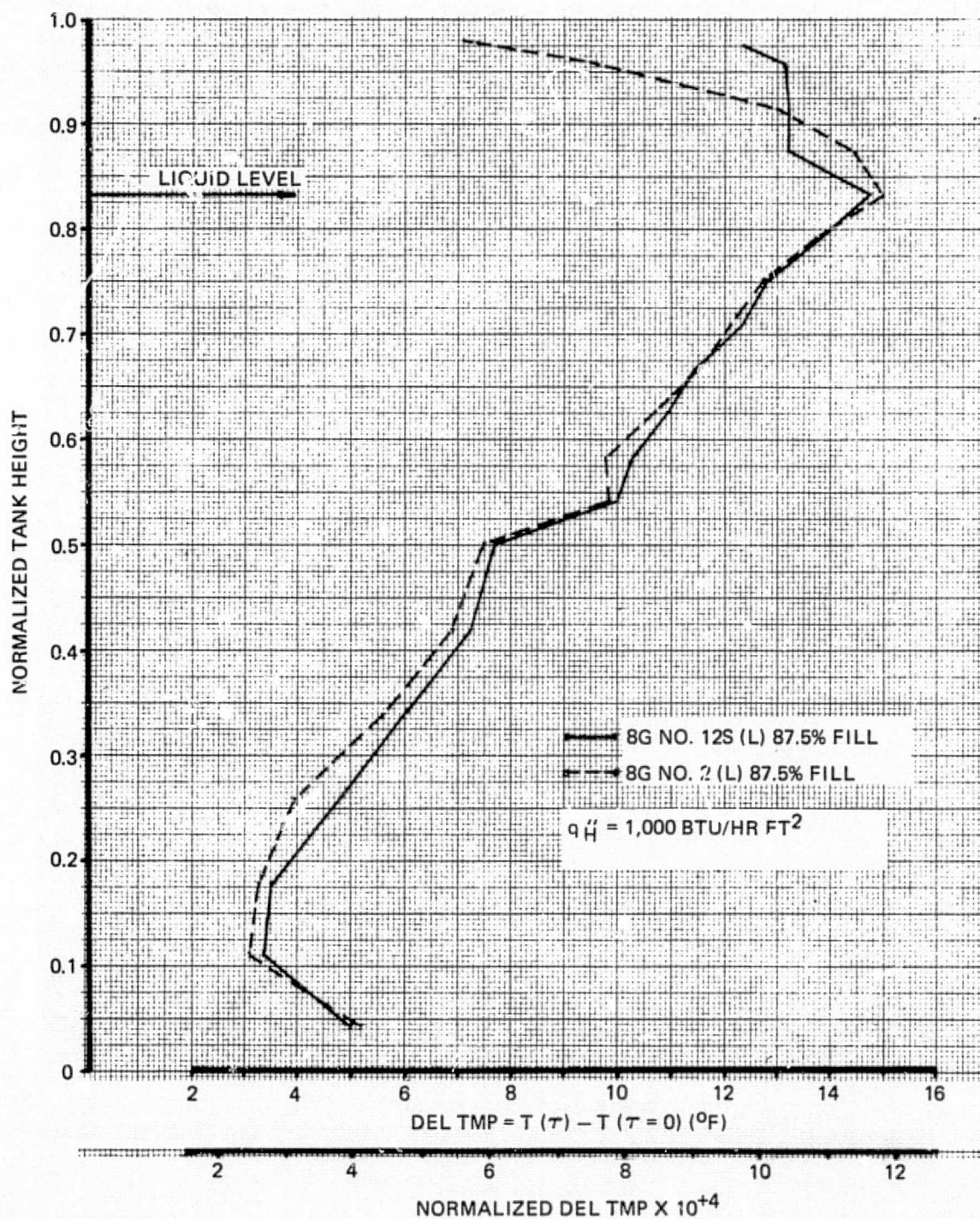


FIGURE 6-16  
 REPRODUCIBILITY DATA  
 6 IN. TANK - STRAT TEMP PROFILES ( $\tau = 1.0$ )  
 TESTS NO. 3 AND NO. 11S (L + U) HEATING

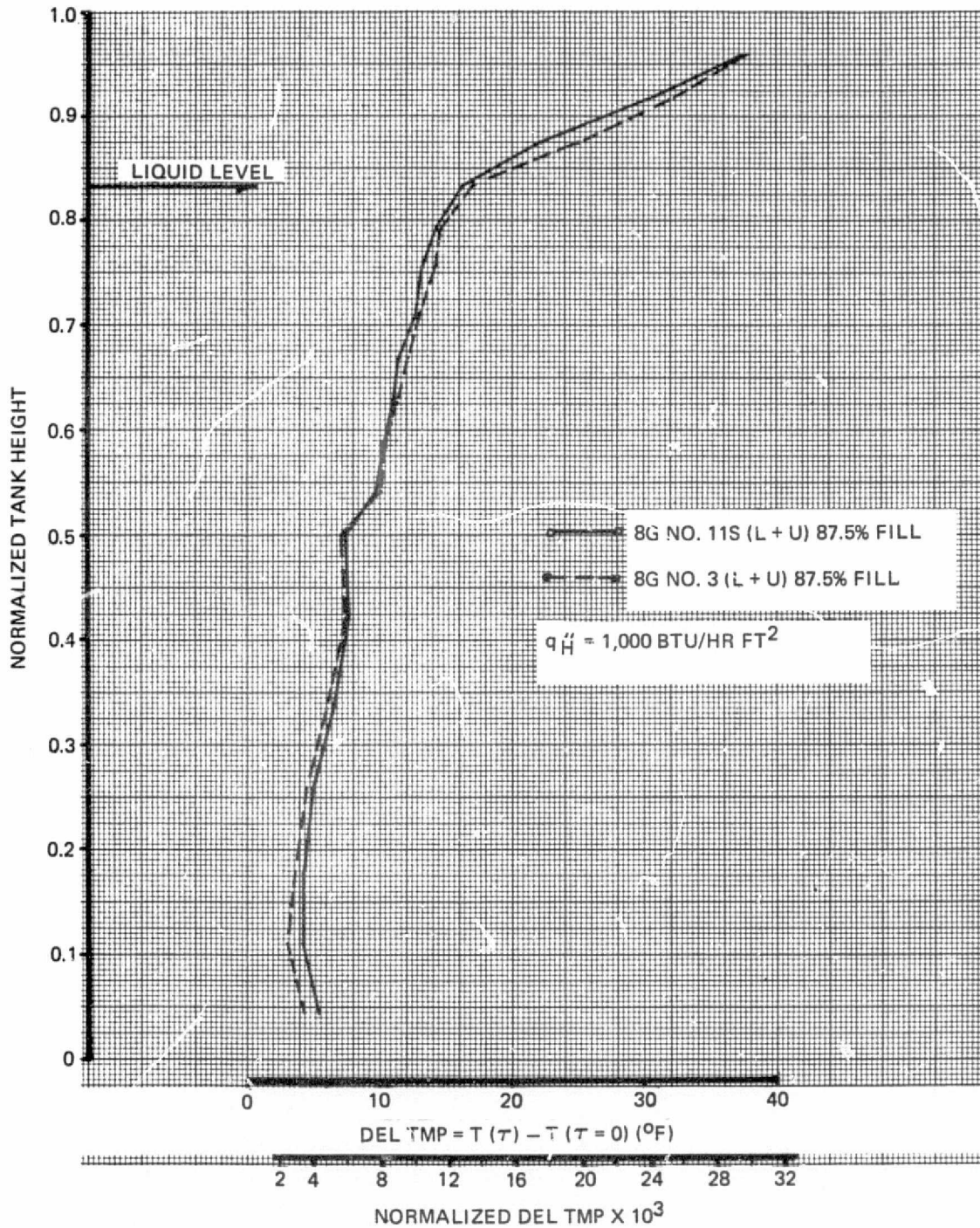




FIGURE 6-17  
 REPRODUCIBILITY DATA  
 6 IN. TANK - STRAT TEMP PROFILES ( $\tau = 1.0$ )  
 TESTS 8G NO. 9S AND NO. 15S (L) HEATING

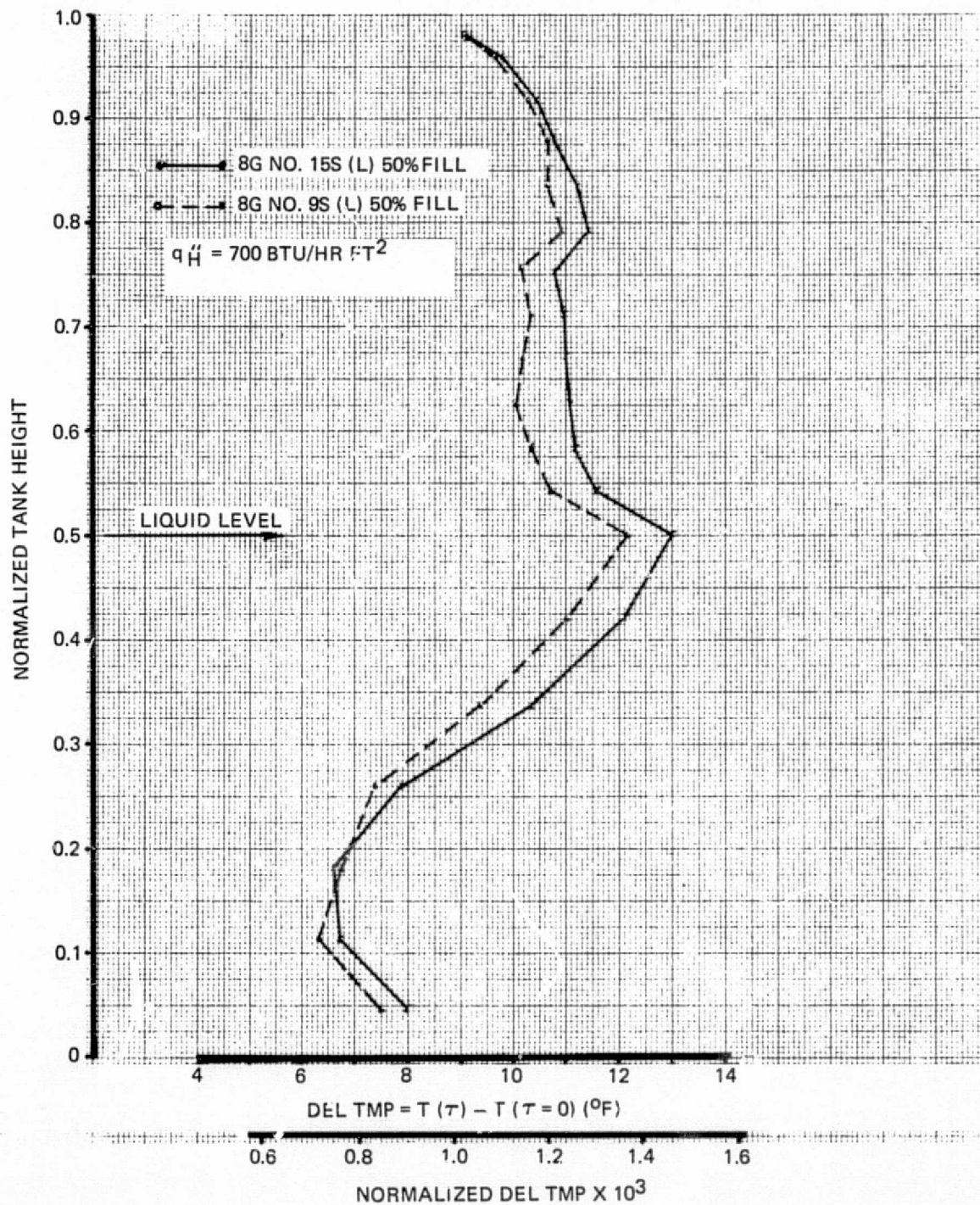


FIGURE 6-18  
 REPRODUCIBILITY DATA  
 6 IN. TANK - STRAT TEMP PROFILES ( $\tau = 1.0$ )  
 TESTS 8G NO. 10S AND NO. 16S (L + U) HEATING

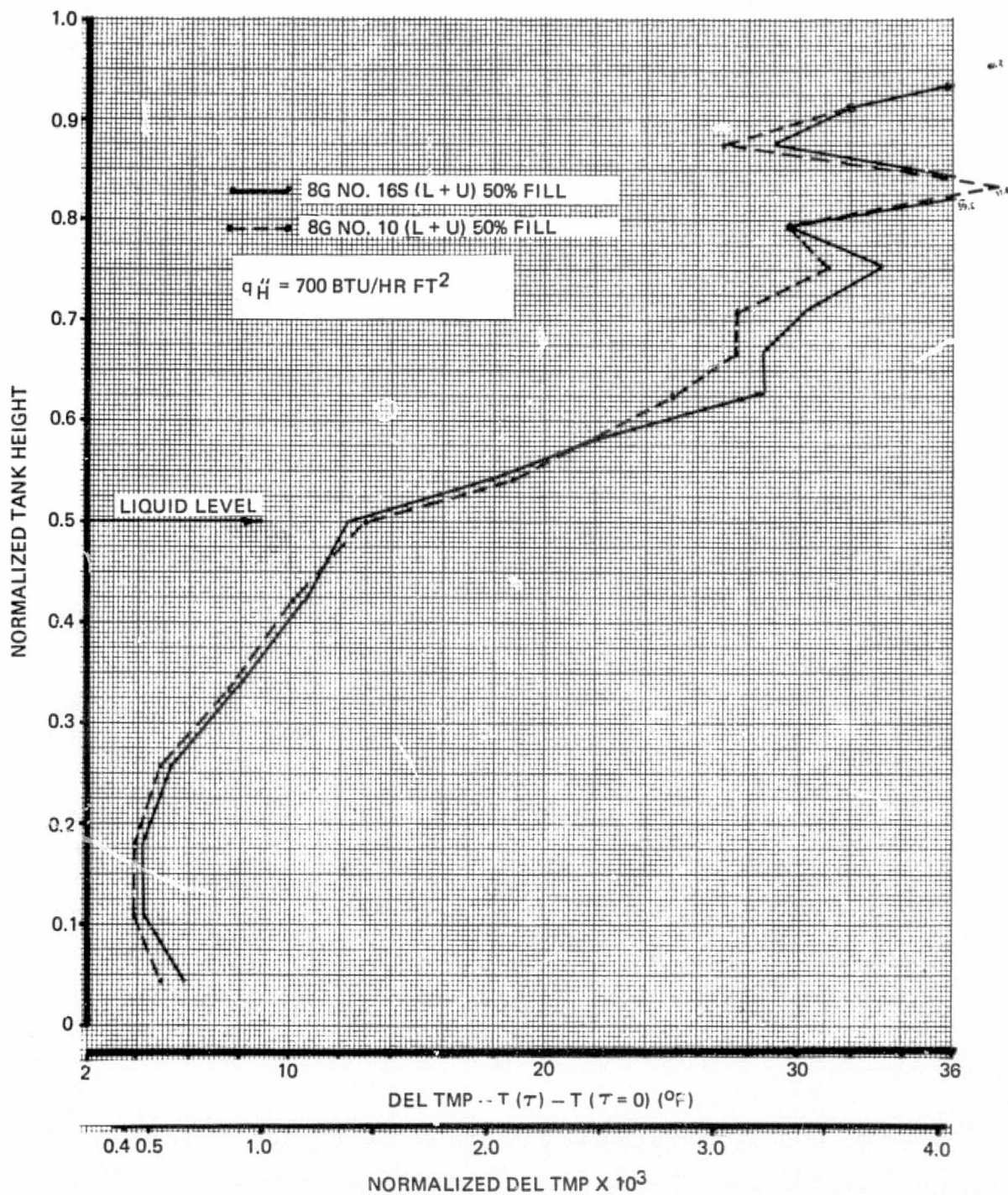


FIGURE 6-19  
REPRODUCIBILITY DATA  
6 IN. TANK - STRAT TEMP PROFILES ( $\tau = 1.0$ )  
TESTS 8G NO. 1, NO. 5, AND NO. 8S (L) HEATING

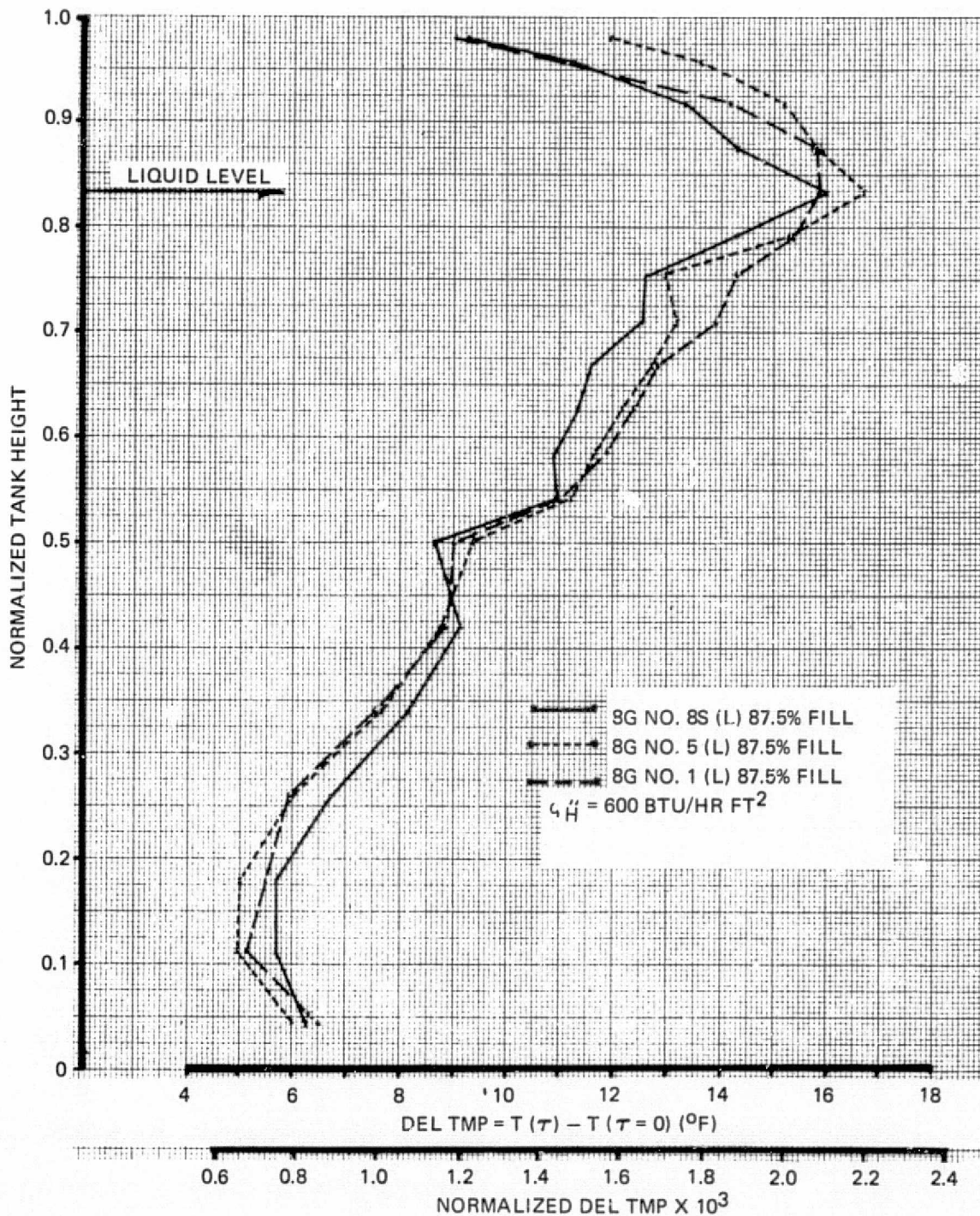




FIGURE 6-20  
 REPRODUCIBILITY DATA  
 6 IN. TANK - STRAT TEMP PROFILES ( $\tau = 1.0$ )  
 TESTS 8G NO. 4 AND NO. 6 (L + U) HEATING

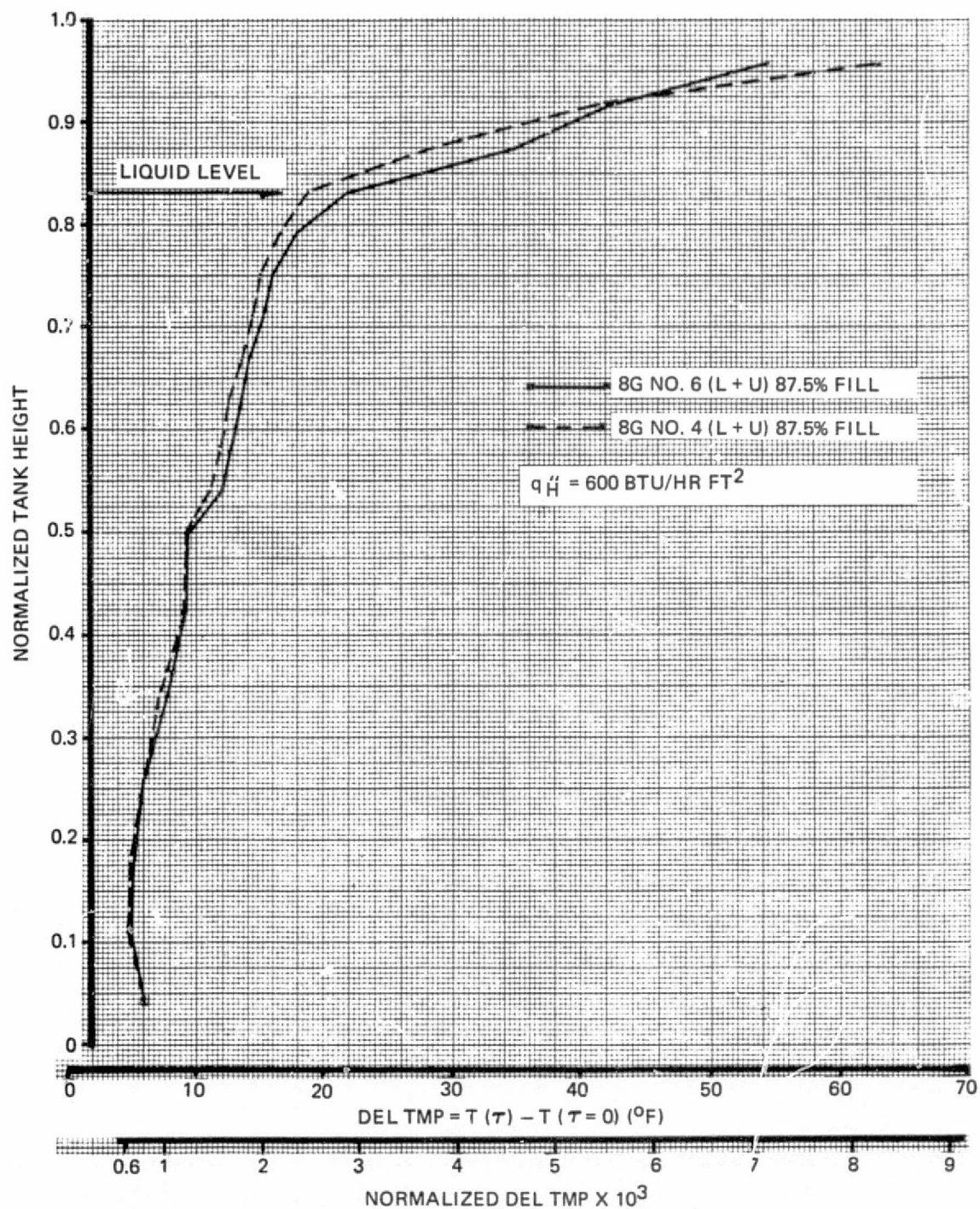


FIGURE 6-21  
 REPRODUCIBILITY DATA  
 12 IN. TANK - STRAT TEMP PROFILES ( $\tau = 1.0$ )  
 TESTS 1G NO. 30 AND NO. 25 (L) HEATING

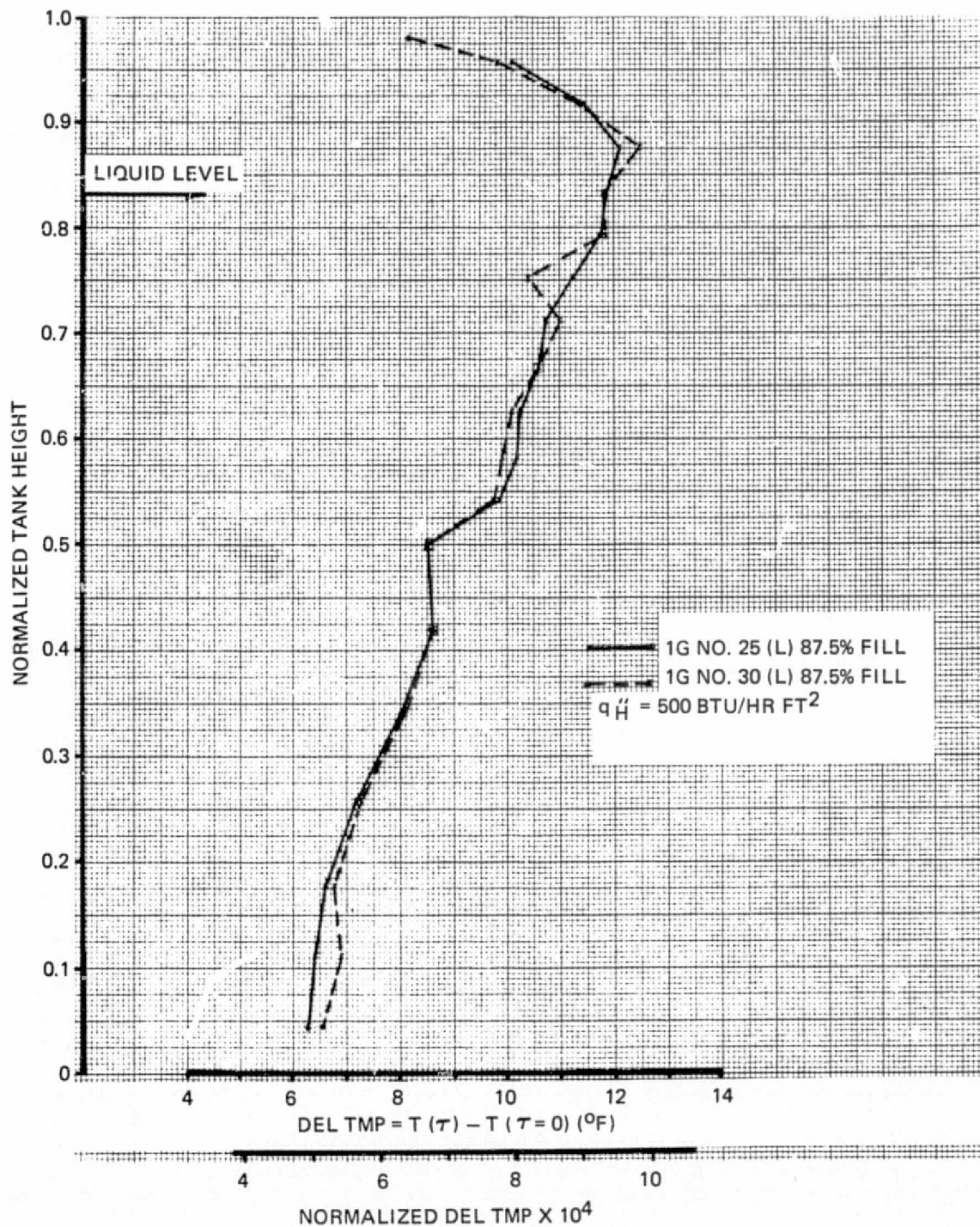


FIGURE 6-22  
REPRODUCIBILITY DATA  
12 IN. TANK - STRAT TEMP PROFILES ( $\tau = 1.0$ )  
TESTS 1G NO. 31 AND NO. 17 (L + U) HEATING

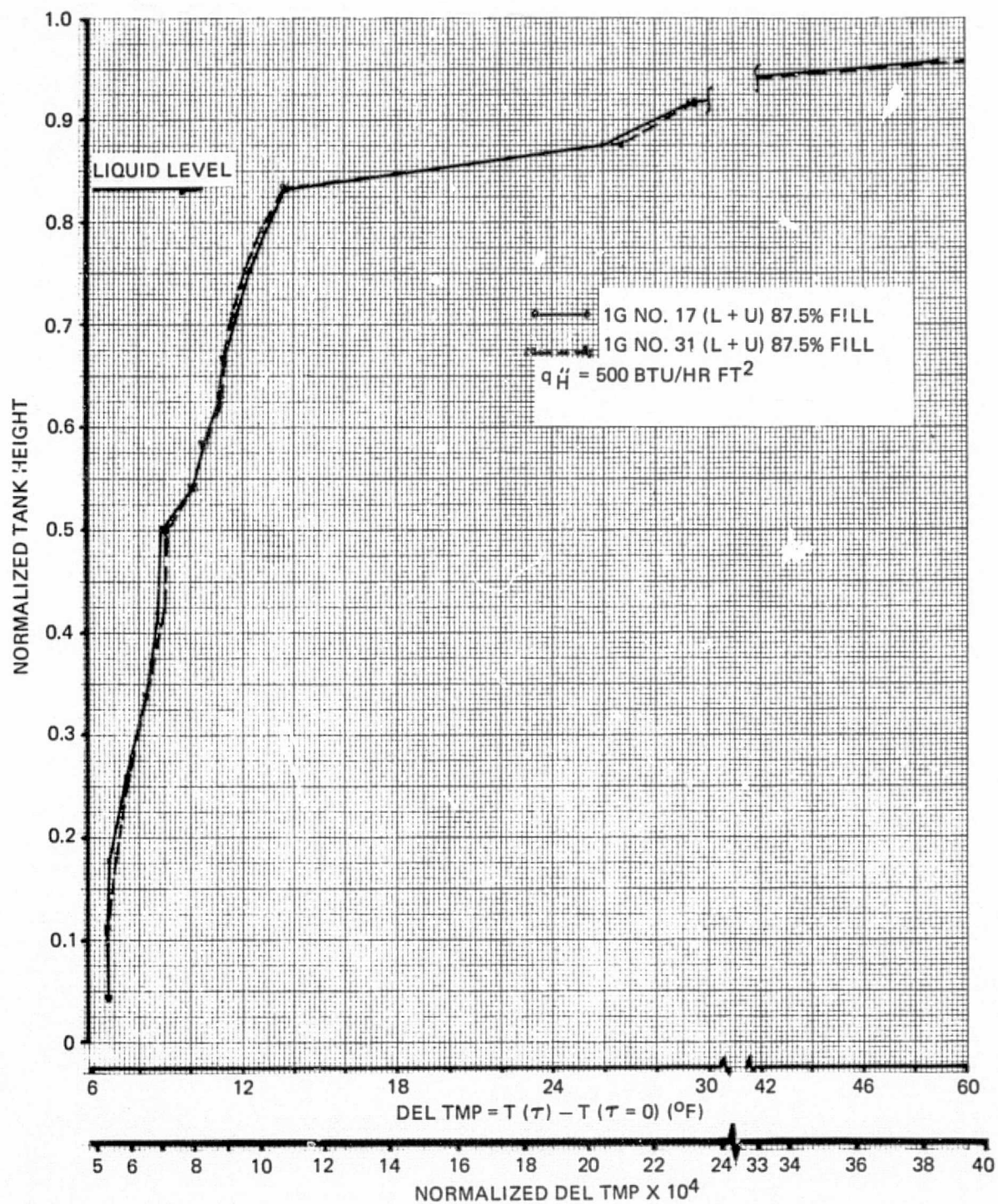




FIGURE 6-23  
 REPRODUCIBILITY DATA  
 12 IN. TANK - STRAT TEMP PROFILES ( $\tau = 1.0$ )  
 TESTS 1G NO. 33 AND NO. 32 (L) HEATING

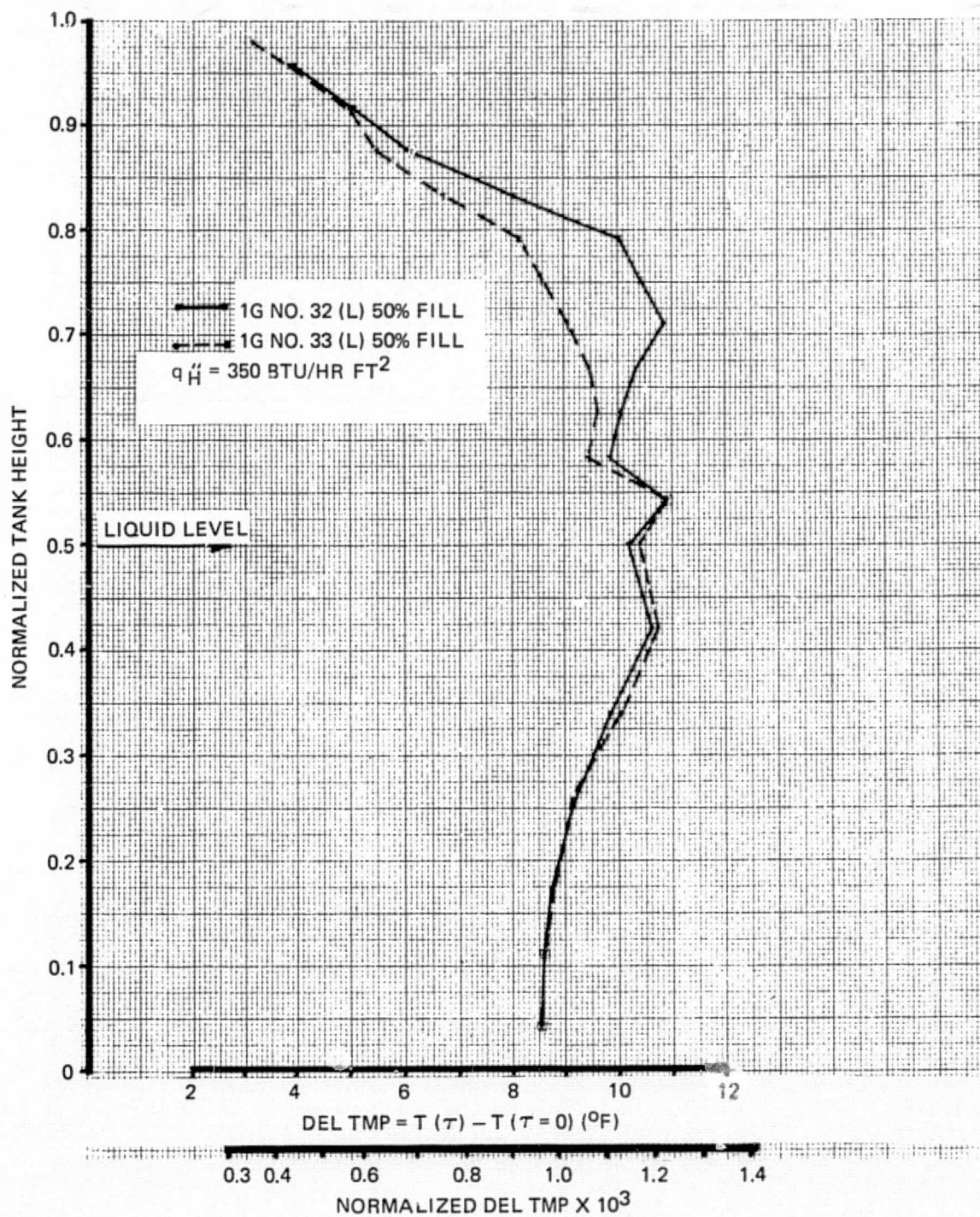


FIGURE 6-24  
 REPRODUCIBILITY DATA  
 12 IN. TANK - STRAT TEMP PROFILES ( $\tau = 1.0$ )  
 TESTS 1G NO. 34 AND NO. 35 (L + U) HEATING

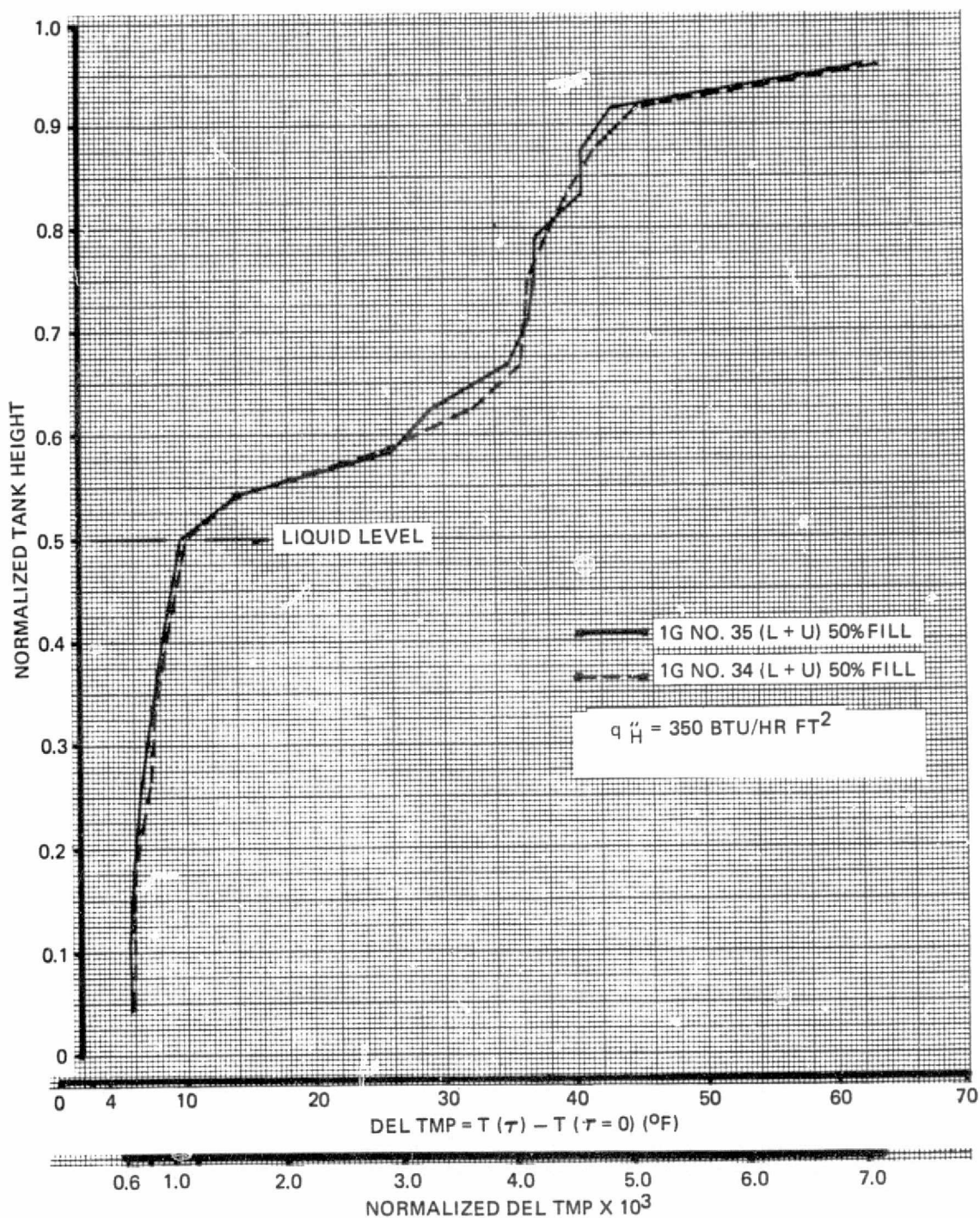
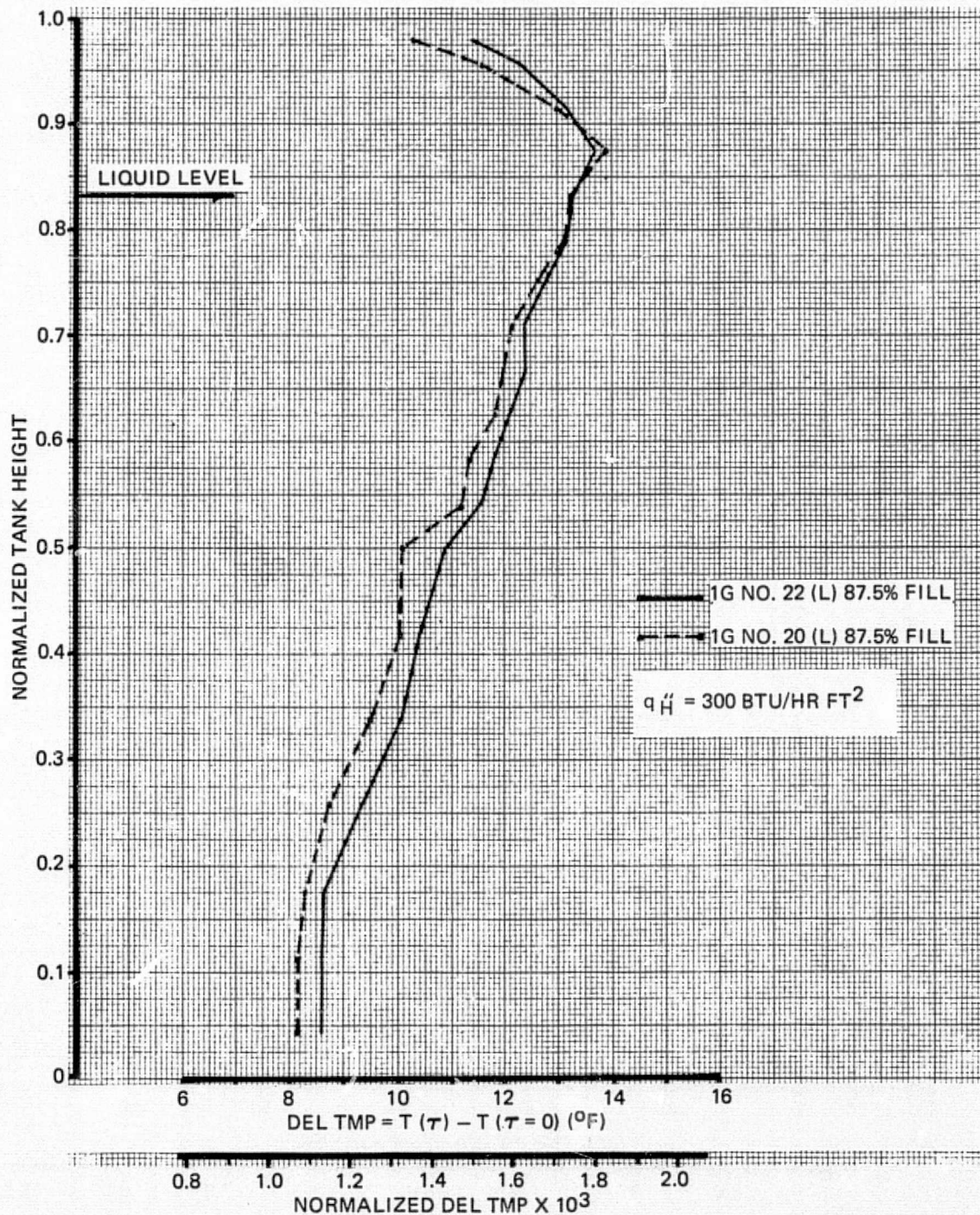




FIGURE 6-25  
 REPRODUCIBILITY DATA  
 12 IN. TANK - STRAT TEMP PROFILES ( $\tau = 1.0$ )  
 TESTS 1G NO. 20 AND NO. 22 (L) HEATING



C-2

FIGURE 6-26  
 REPRODUCIBILITY DATA  
 12 IN. TANK - STRAT TEMP PROFILES ( $\tau = 1.0$ )  
 TESTS 1G NO. 23 AND NO. 28 (L + U) HEATING

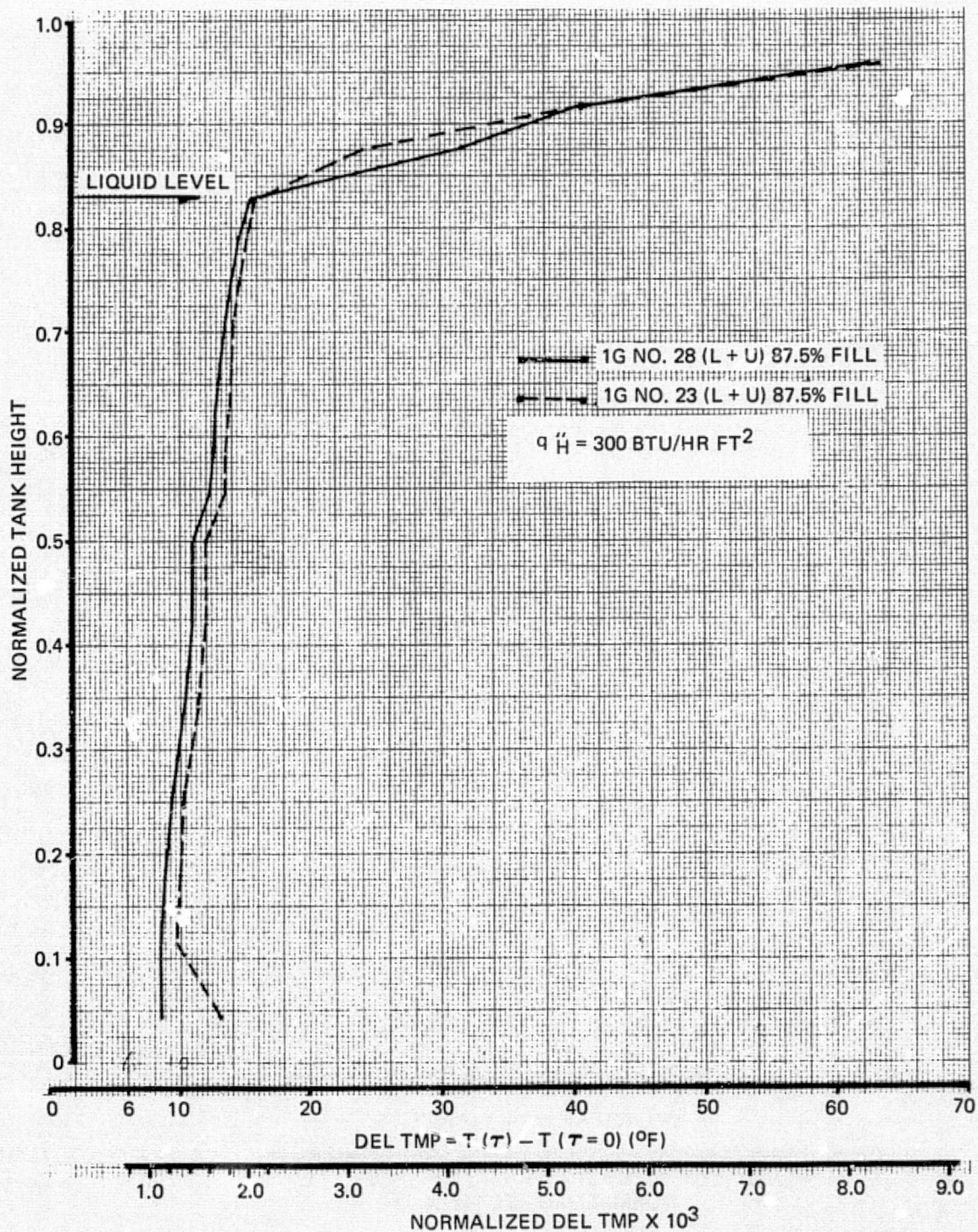




FIGURE 6-27  
 REPRODUCIBILITY DATA  
 12 IN. TANK - STRAT TEMP PROFILES ( $\tau = 1.0$ )  
 TESTS 1G NO. 26 AND NO. 15 (L) HEATING

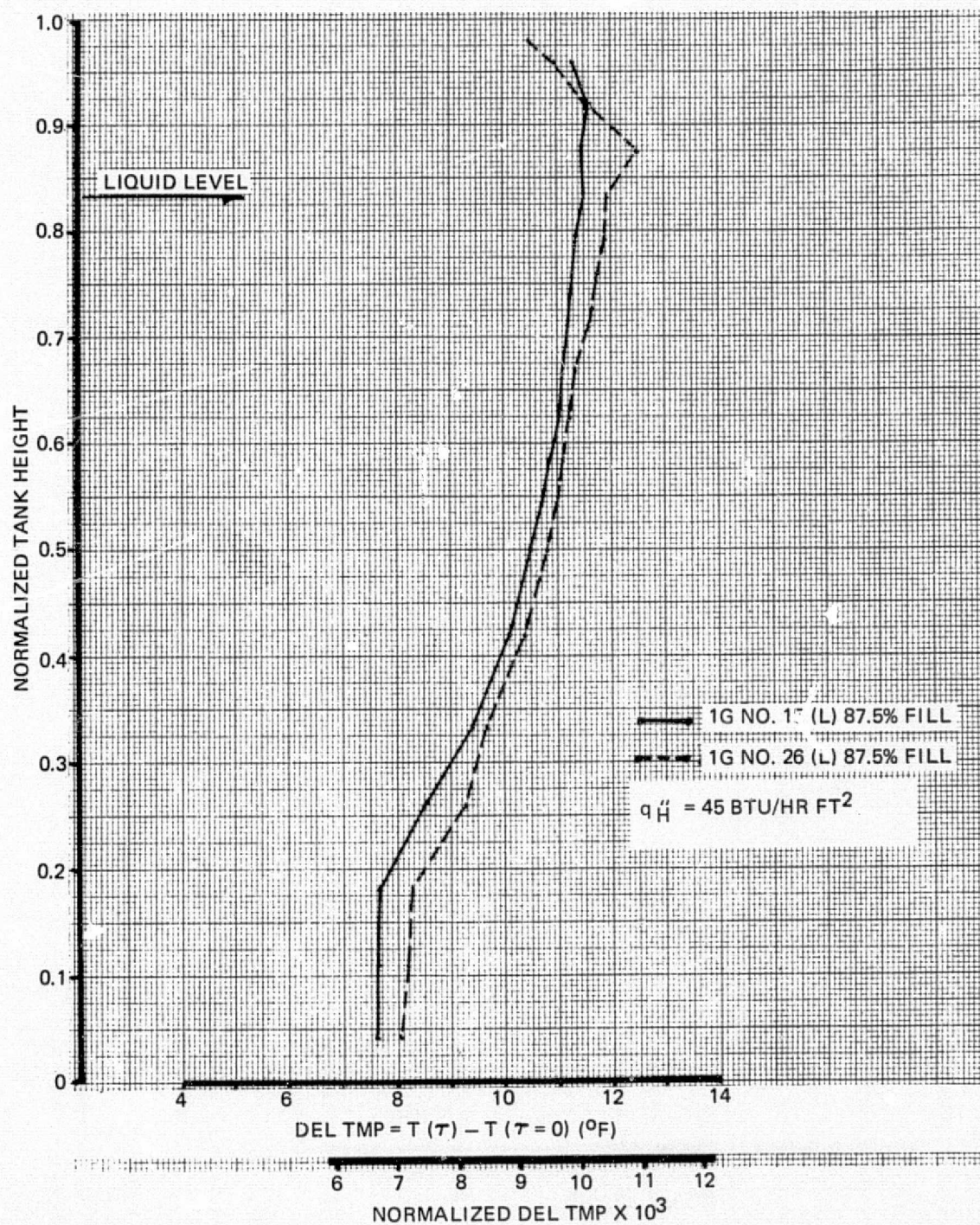


FIGURE 6-28  
 REPRODUCIBILITY DATA  
 18 IN. TANK - STRAT TEMP PROFILES ( $\tau = 1.0$ )  
 TESTS 1G NO. BS AND NO. D (L) HEATING

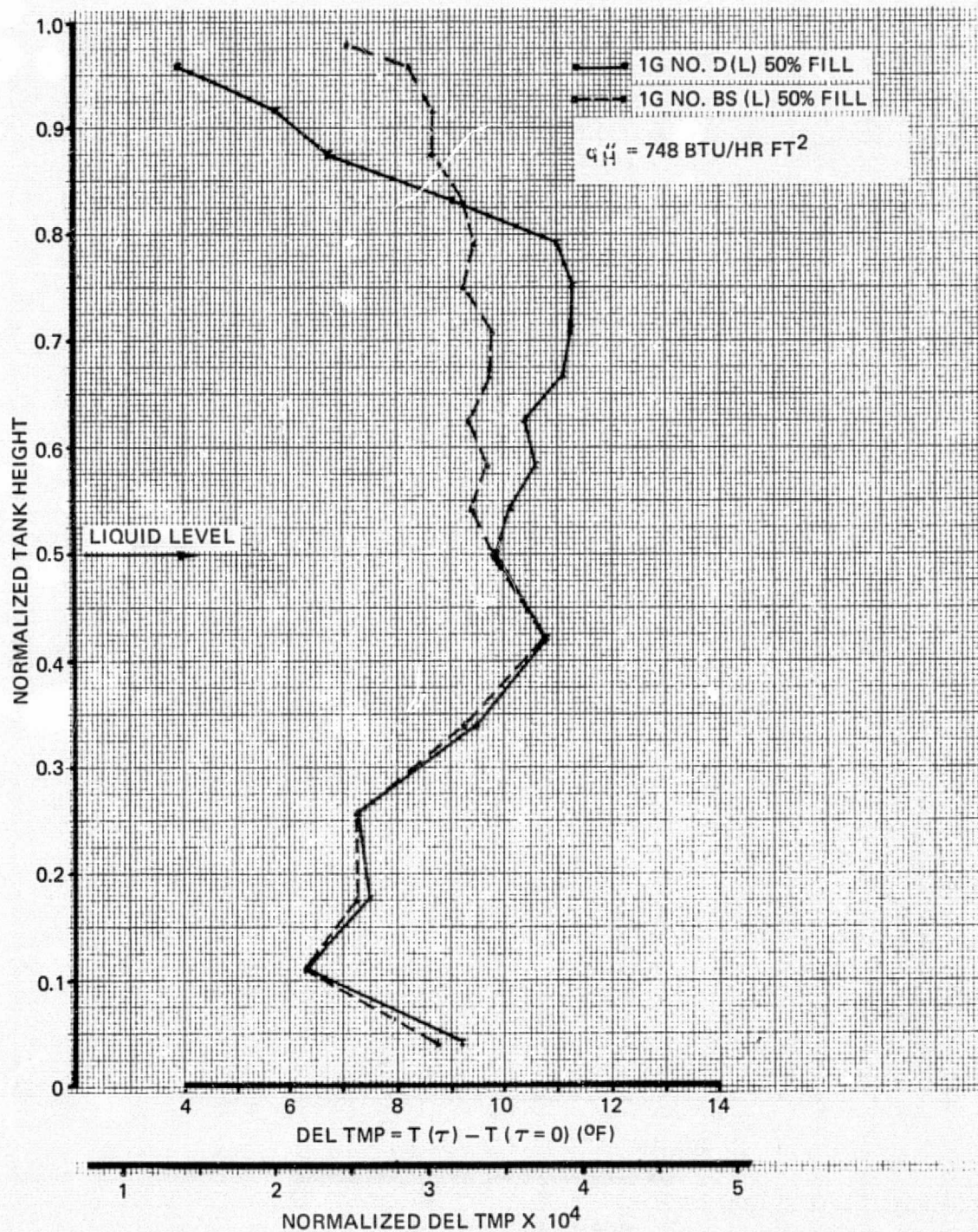




FIGURE 6-29  
REPRODUCIBILITY DATA  
18 IN. TANK - STRAT TEMP PROFILES  
TESTS 1G NO. (F-6-18), NO. BS, AND NO. D

CR 108-1

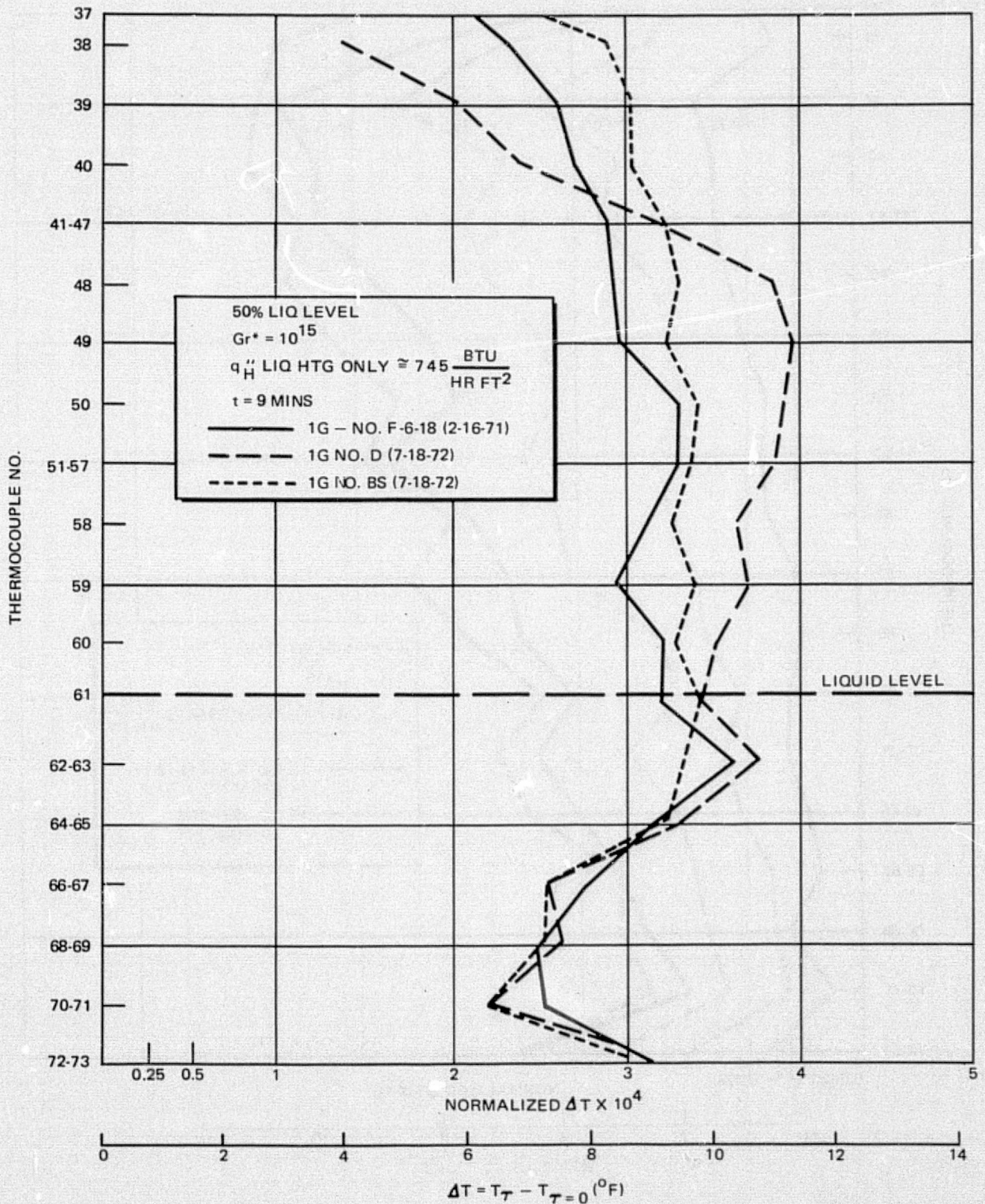


FIGURE 6-30  
REPRODUCIBILITY DATA  
18 IN. TANK - STRAT TEMP PROFILES ( $\tau = 1.0$ )  
TESTS 1G NO. (F-3-18), AND NO. IS

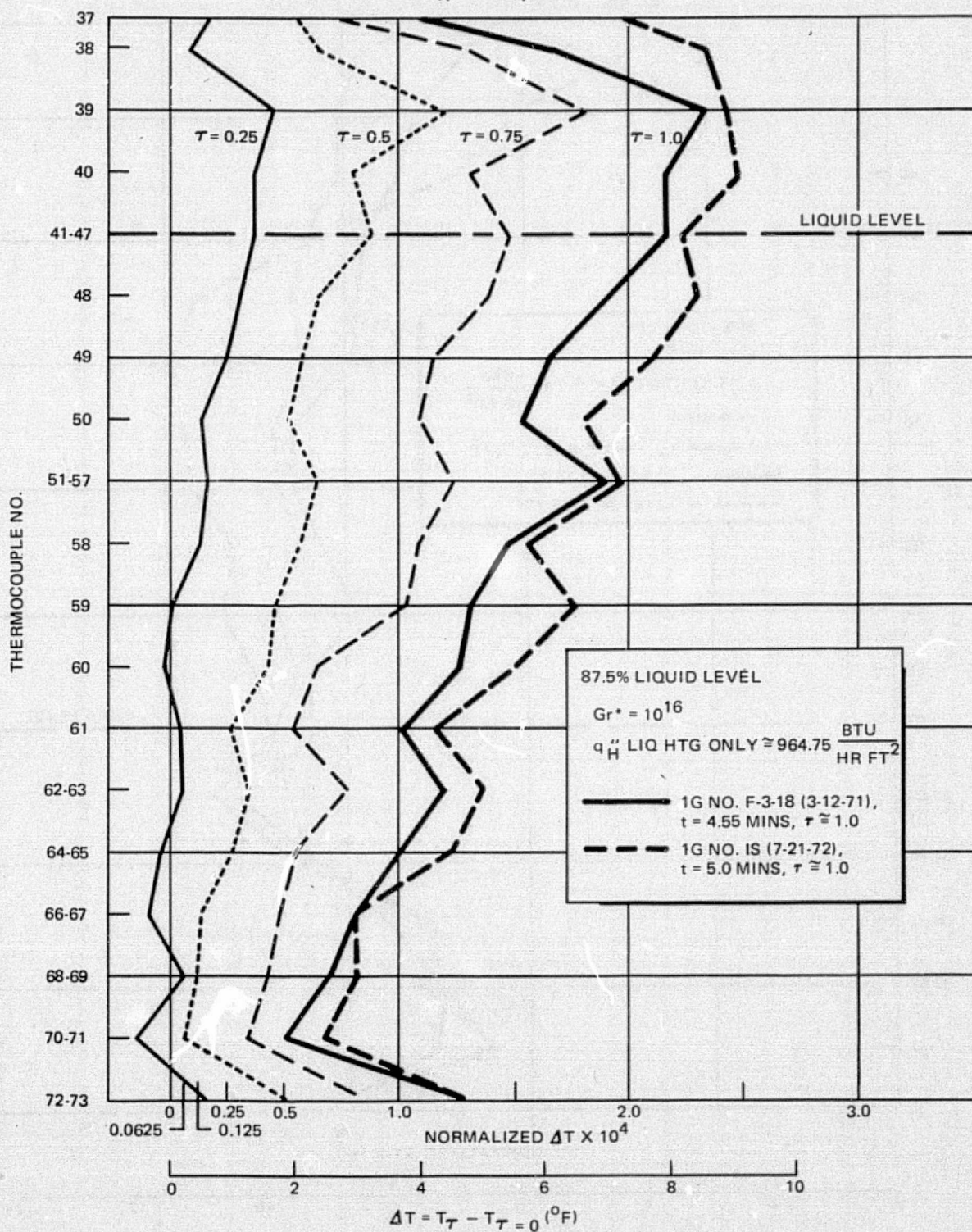
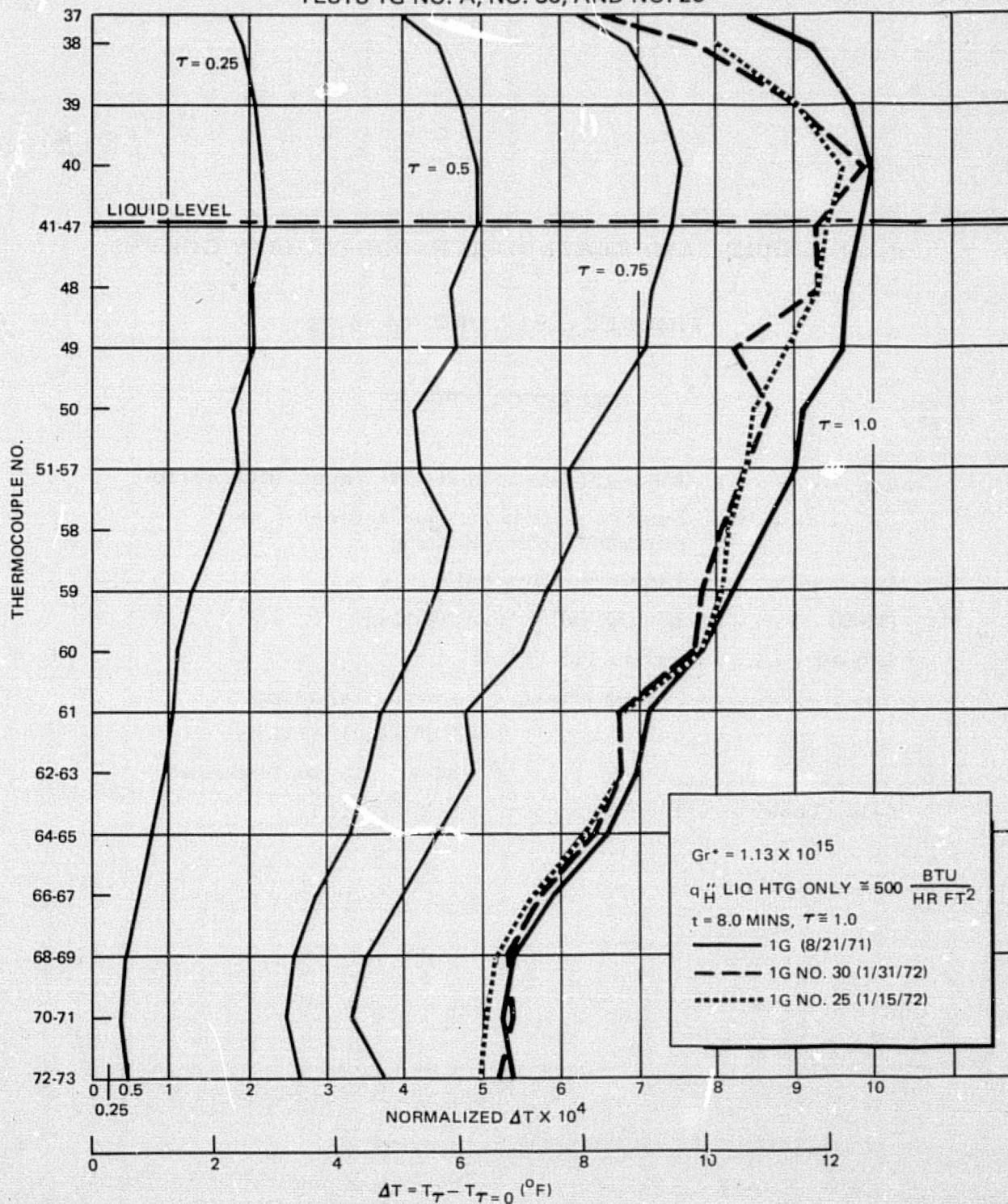




FIGURE 6-31  
REPRODUCIBILITY DATA  
12 IN. TANK - STRAT TEMP PROFILES ( $\tau = 1.0$ )  
TESTS 1G NO. A, NO. 30, AND NO. 25



## BULK LIQUID TEMPERATURE REPRODUCIBILITY CURVES

FIGURES 6-32 THROUGH 6-45

## NOMENC LATURE

 $q_H''$  . . . . . Measured heat heat-flux input, Btu/hr-ft<sup>2</sup>

"s" . . . . . Symbol in test number indicates no  
destratification heating

(L). . . . . Liquid heating only

(L+U) . . . . . Liquid and ullage heating

Liquid . . . . . Freon 113 (PCA)

$$\tau \dots \dots \dots = (t/\theta) \text{ where } \tau = \text{Normalized time}$$

t = Elapsed test time

 $\theta$  = Stratification test time

6-In. Tank. . . . Title refers to tank diameter



FIGURE 6-32  
REPRODUCIBILITY DATA  
6 IN. TANK - BULK LIQUID TEMP HISTORIES  
TESTS 8G NO. 2 AND NO. 12S

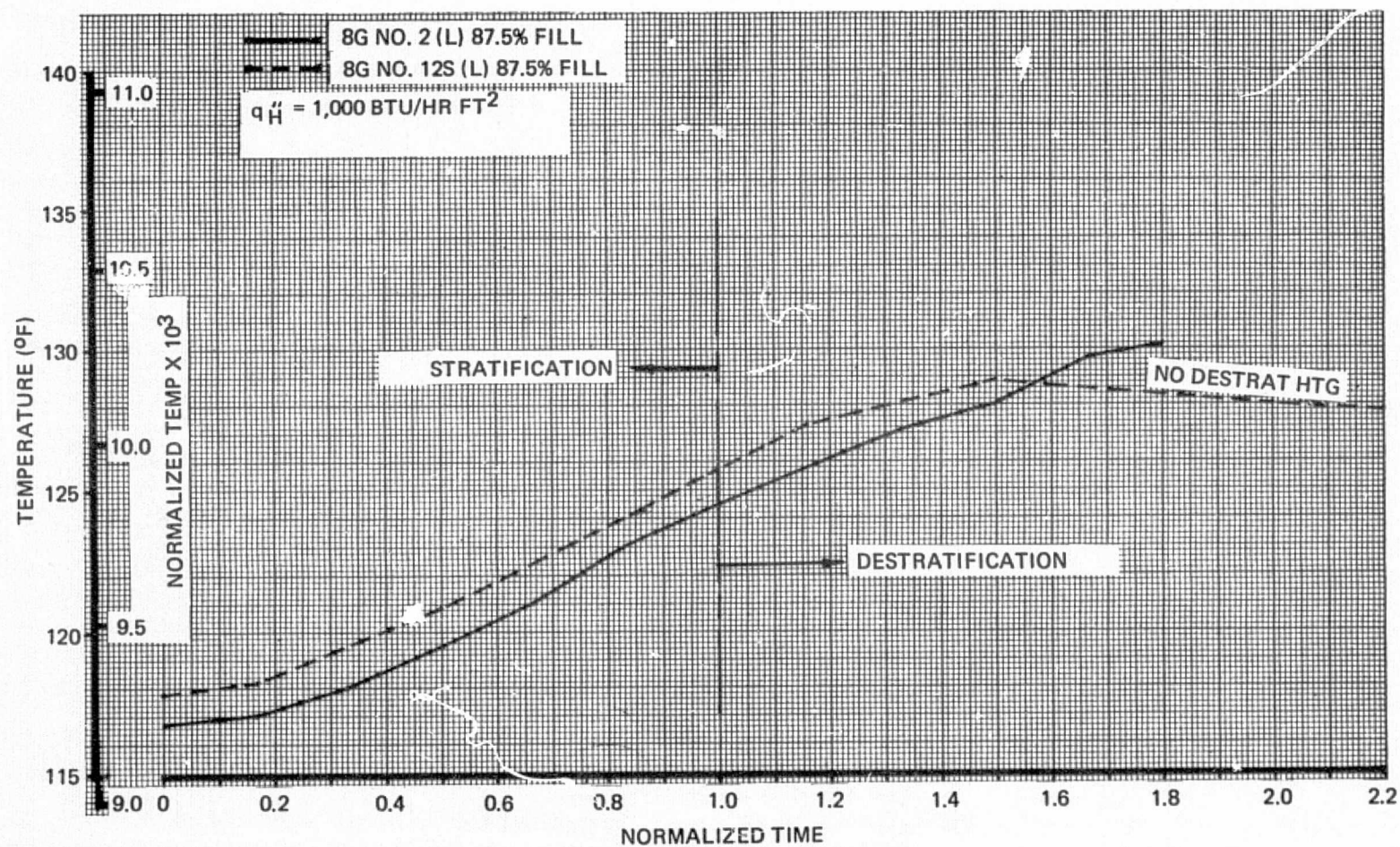


FIGURE 6-33  
REPRODUCIBILITY DATA  
6 IN. TANK - BULK LIQUID TEMP HISTORIES  
TESTS 8G NO. 3 AND NO. 11S

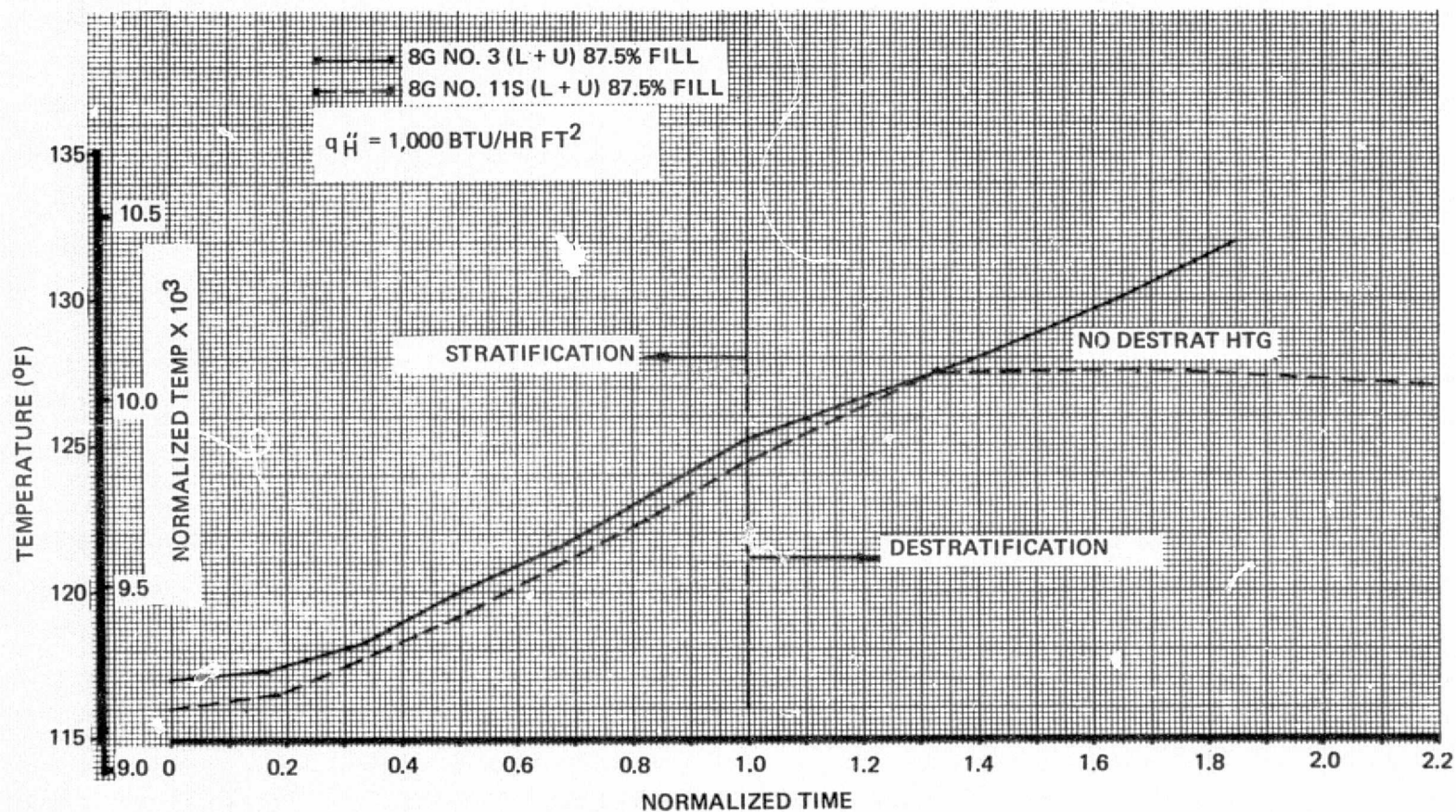


FIGURE 6-34  
REPRODUCIBILITY DATA  
6 IN. TANK - BULK LIQUID TEMP HISTORIES  
TESTS 8G NO. 9S AND NO. 15S

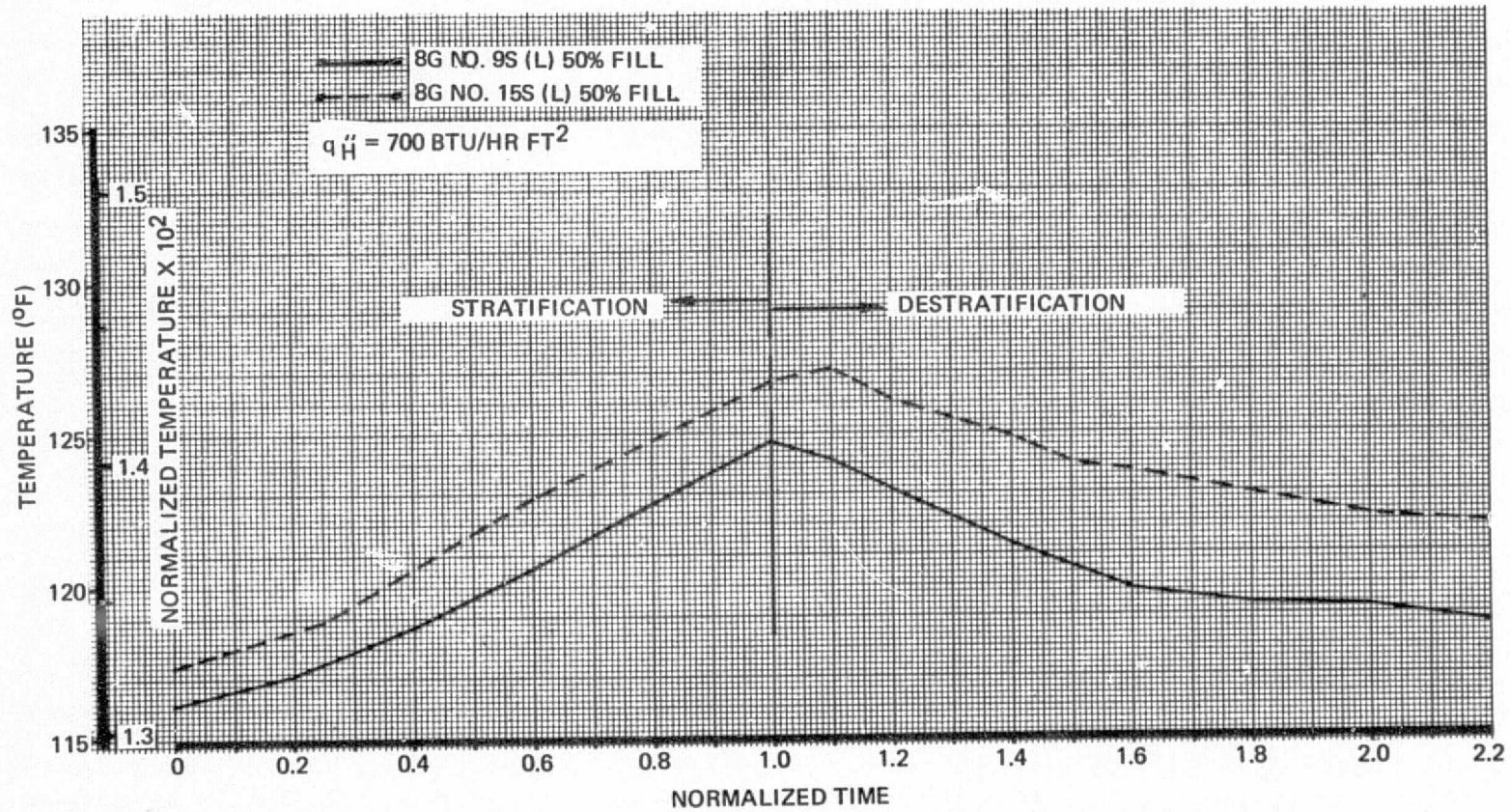




FIGURE 6-35  
 REPRODUCIBILITY DATA  
 6 IN. TANK - BULK LIQUID TEMP HISTORIES  
 TESTS 8G NO. 10S AND NO. 16S

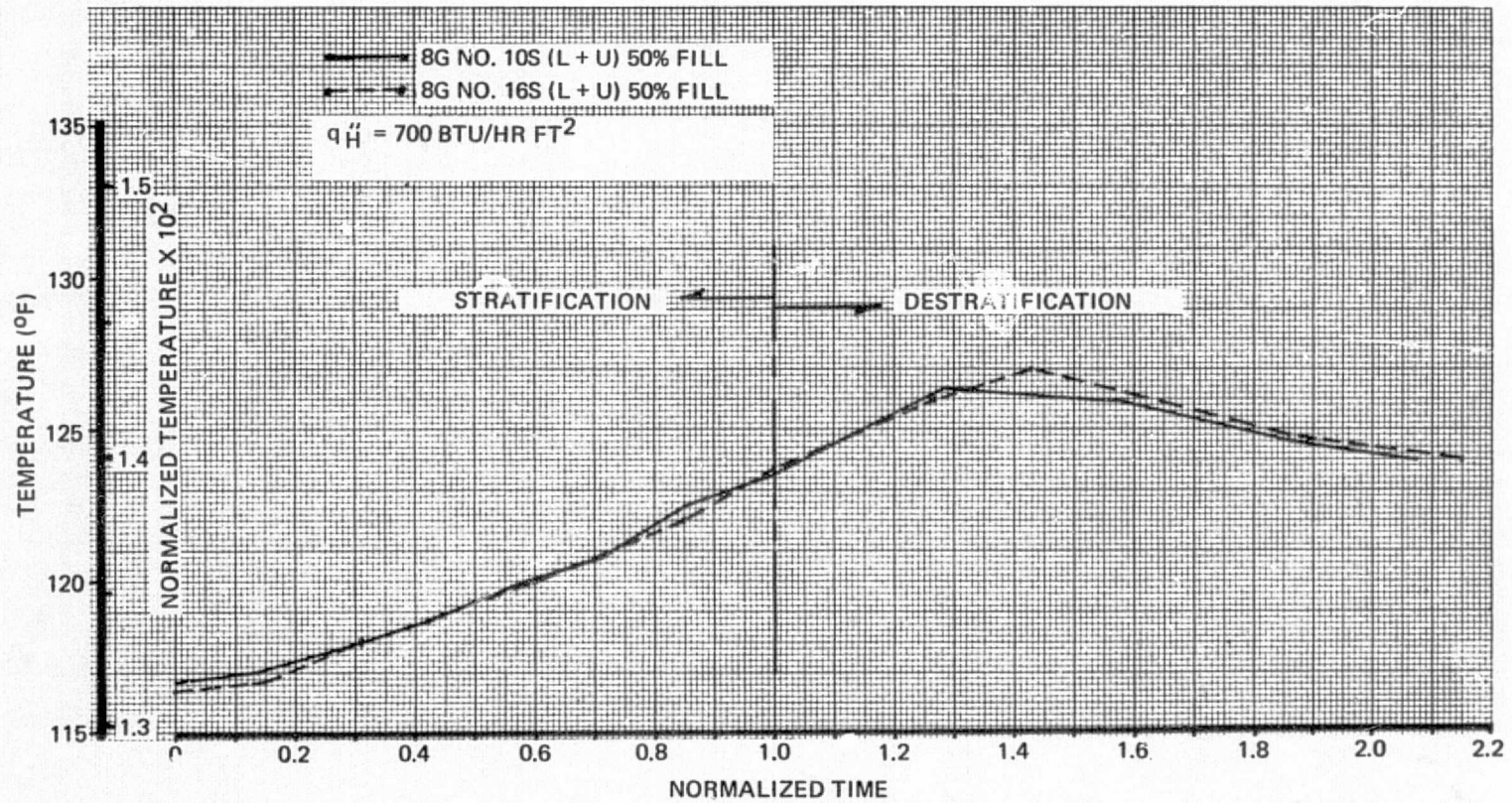


FIGURE 6-36  
REPRODUCIBILITY DATA  
6 IN. TANK - BULK LIQUID TEMP HISTORIES  
TESTS 8G NO. 1, NO. 5, AND NO. 8S

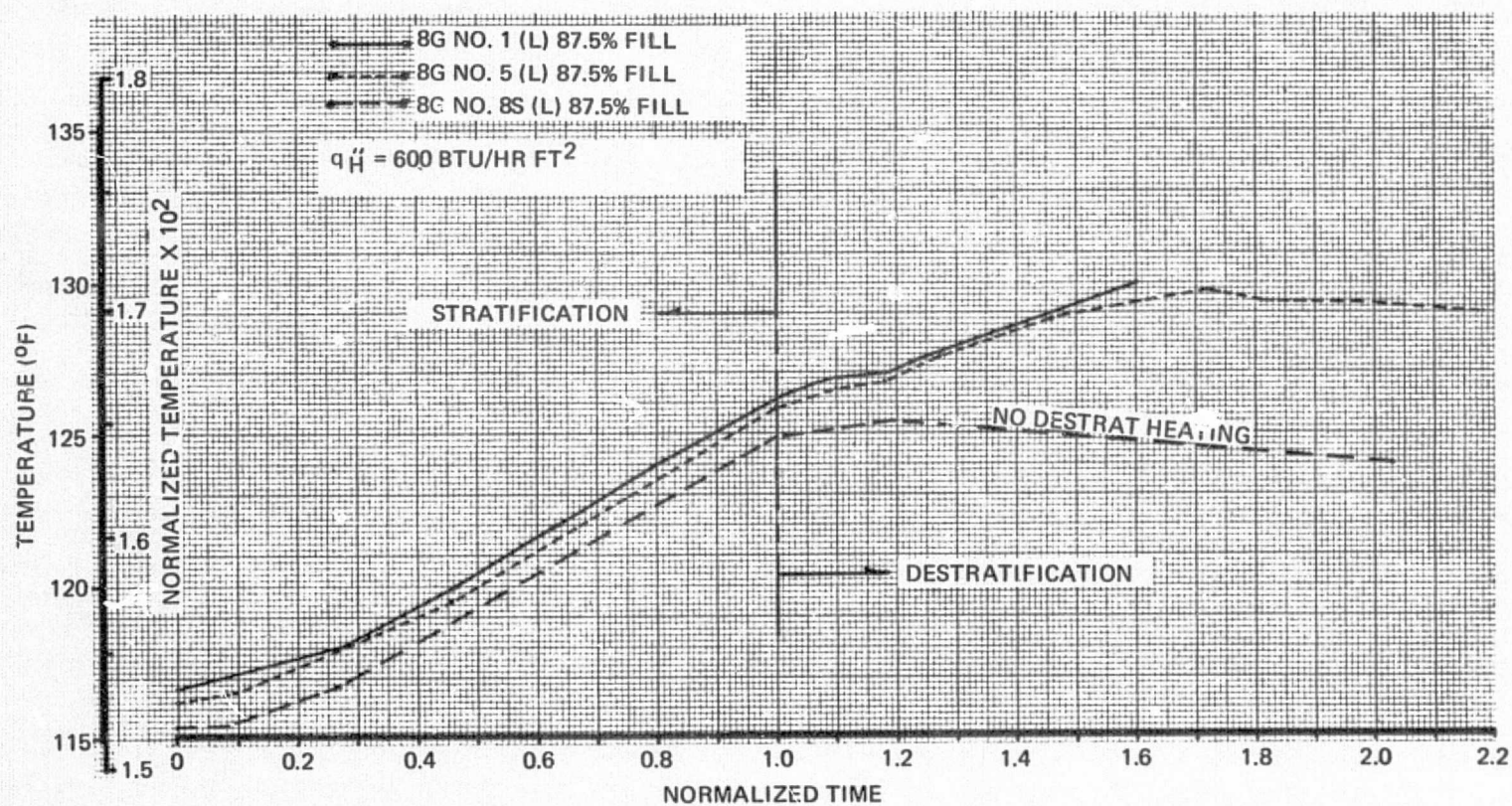


FIGURE 6-37  
REPRODUCIBILITY DATA  
6 IN. TANK - BULK LIQUID TEMP HISTORIES  
TESTS 8G NO. 4 AND NO. 6

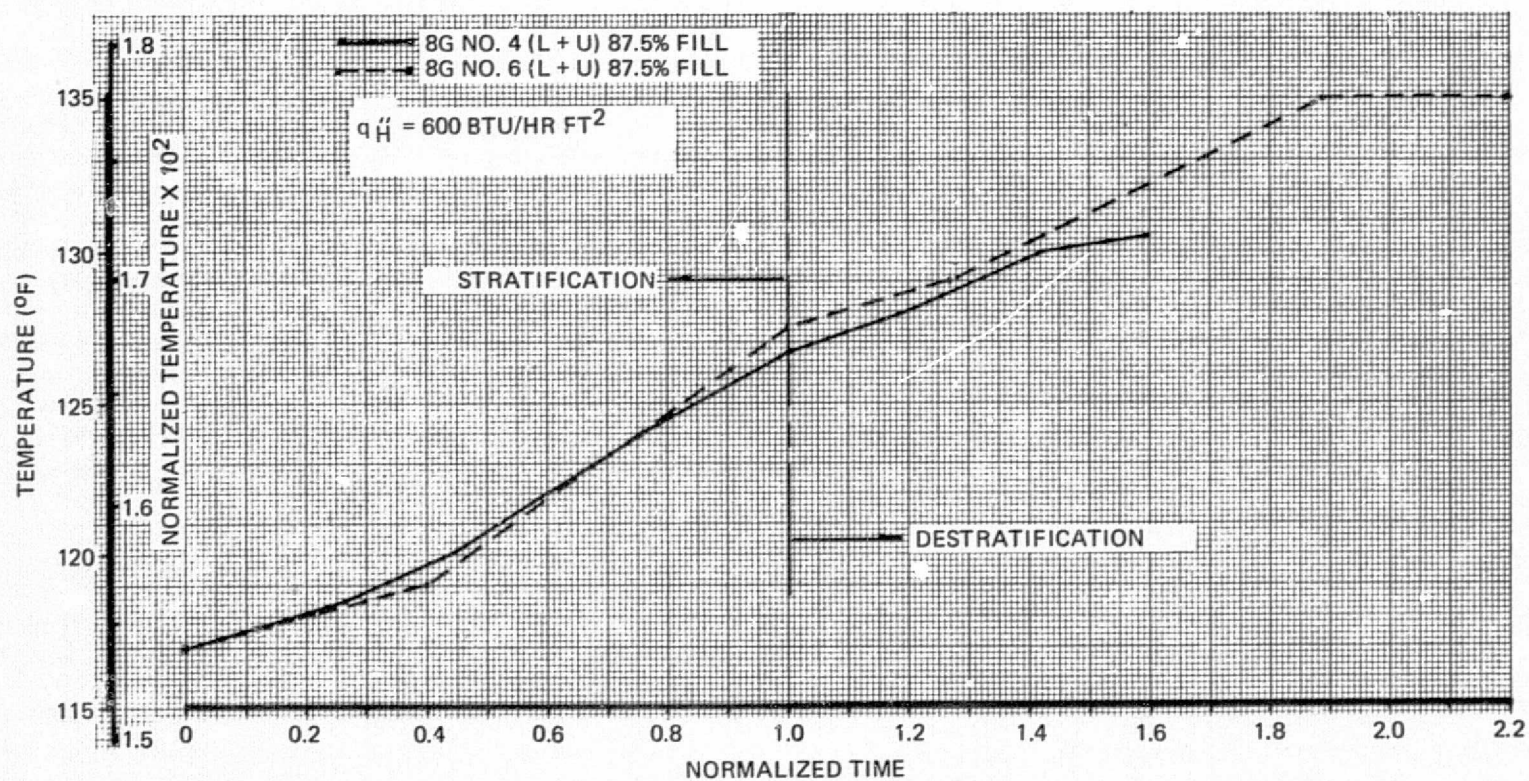




FIGURE 6-38  
REPRODUCIBILITY DATA  
12 IN. TANK - BULK LIQUID TEMP HISTORIES  
TESTS 1G NO. 30 AND NO. 25

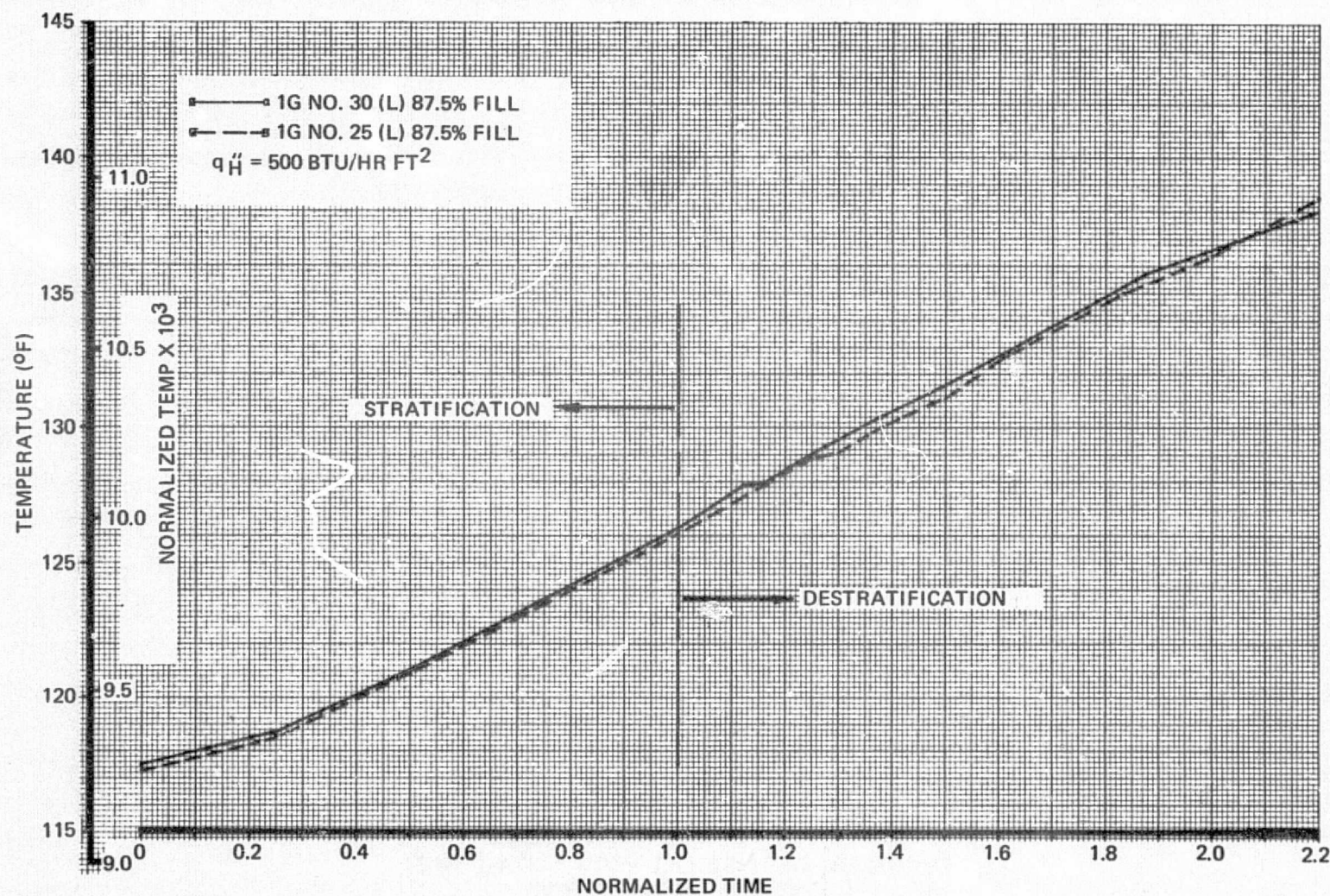




FIGURE 6-39  
REPRODUCIBILITY DATA  
12 IN. TANK - BULK LIQUID TEMP HISTORIES  
TESTS 1G NO. 31 AND NO. 17

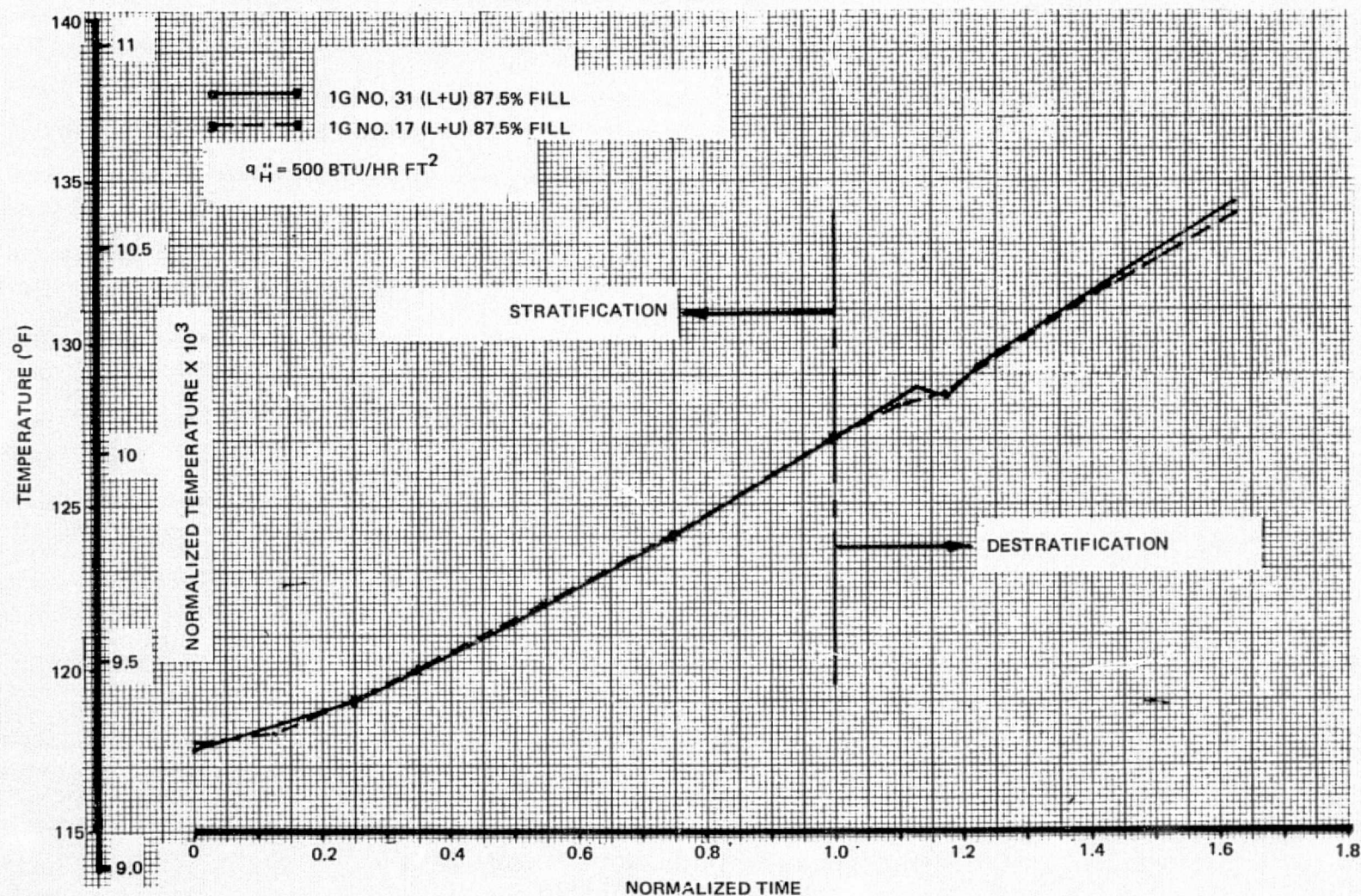


FIGURE 6-40  
REPRODUCIBILITY DATA  
12 IN. TANK - BULK LIQUID TEMP HISTORIES  
TESTS 1G NO. 33 AND NO. 32

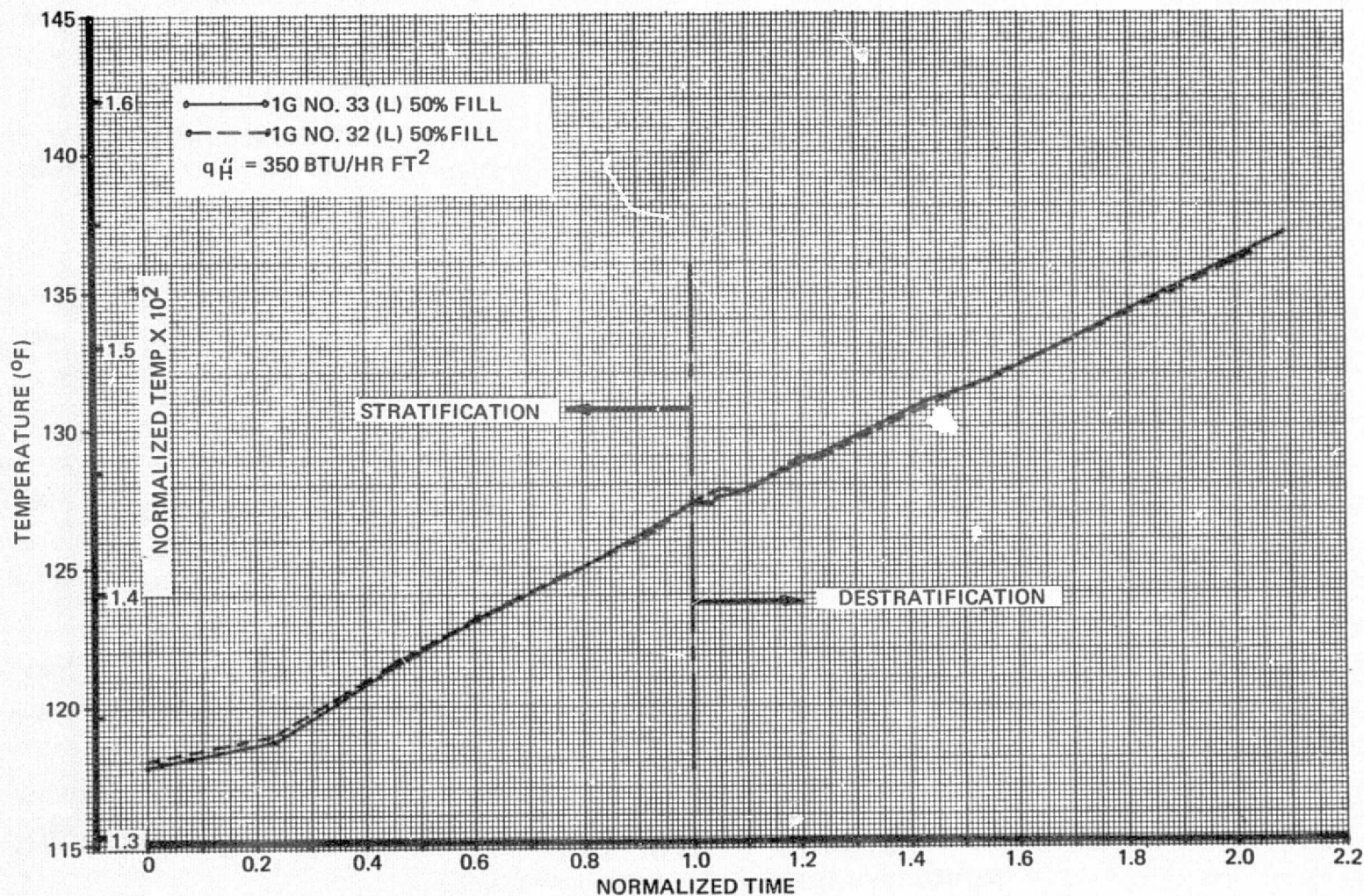




FIGURE 6-41  
REPRODUCIBILITY DATA  
12 IN. TANK - BULK LIQUID TEMP HISTORIES  
TESTS 1G NO. 34 AND NO. 35

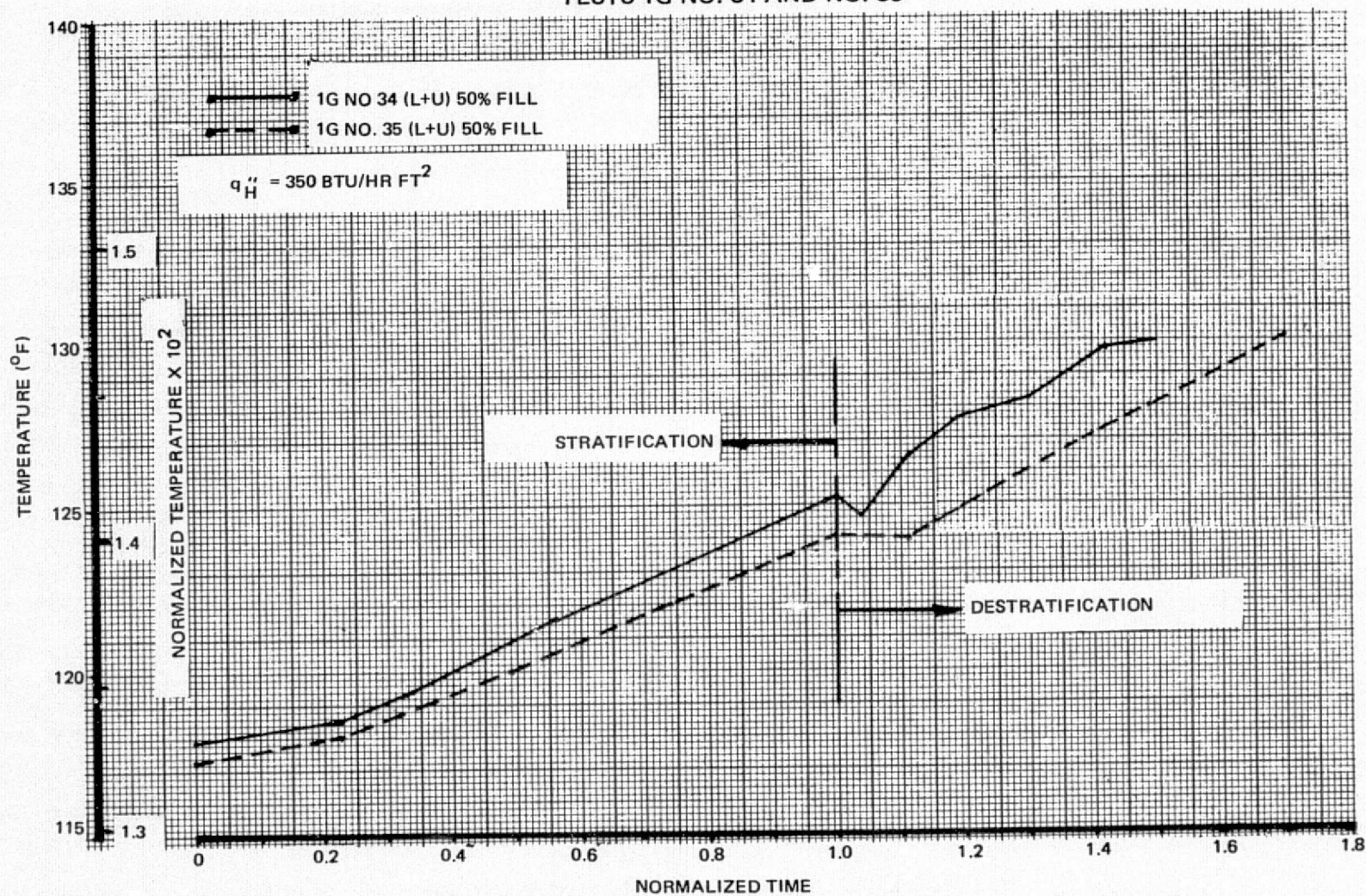


FIGURE 6-42  
REPRODUCIBILITY DATA  
12-IN. TANK - BULK LIQUID TEMP HISTORIES  
TESTS 1G NO. 20 AND NO. 22

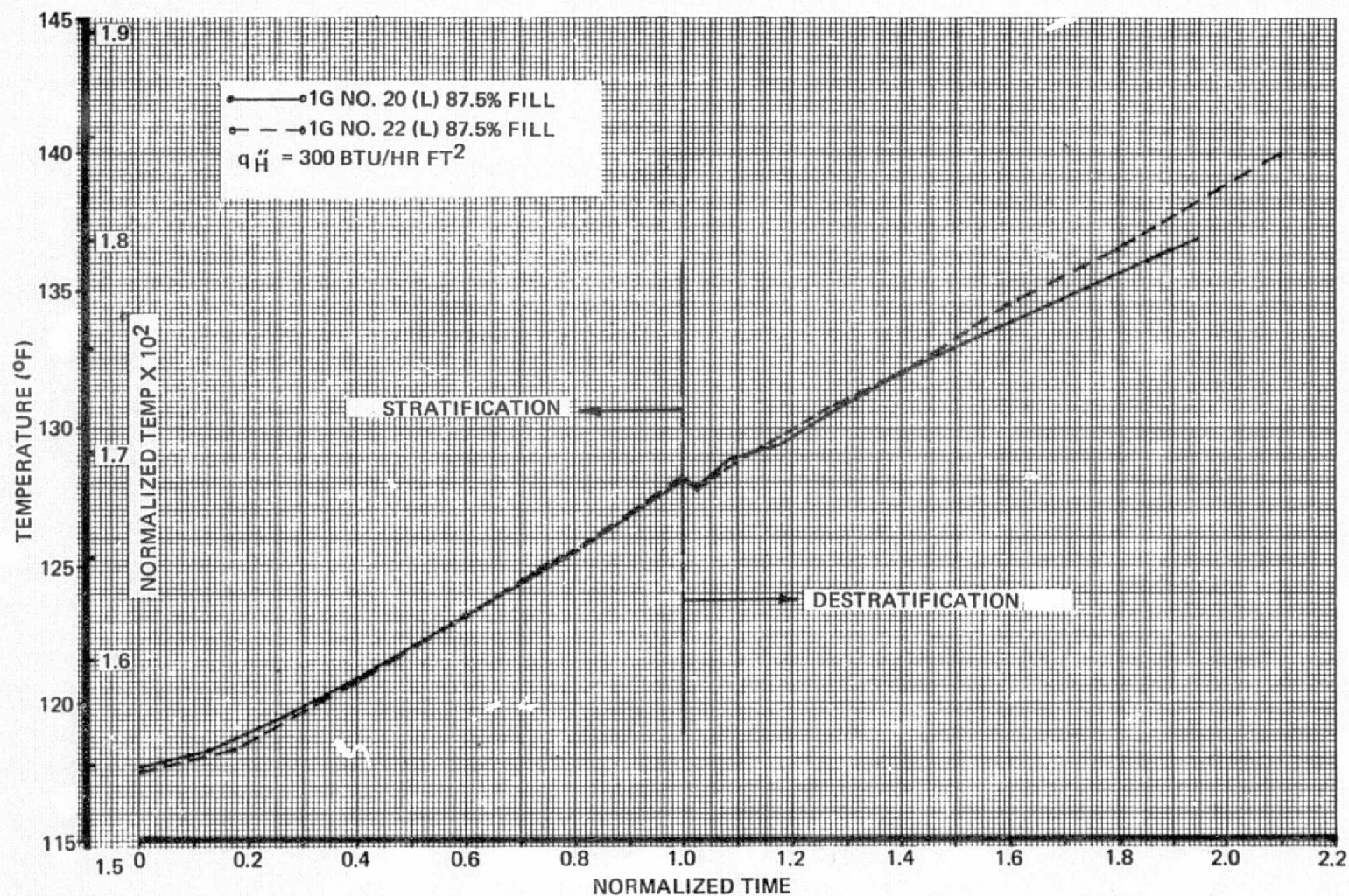




FIGURE 6-43  
REPRODUCIBILITY DATA  
12 IN. TANK - BULK LIQUID TEMP HISTORIES  
TESTS 1G NO. 23 AND NO. 28

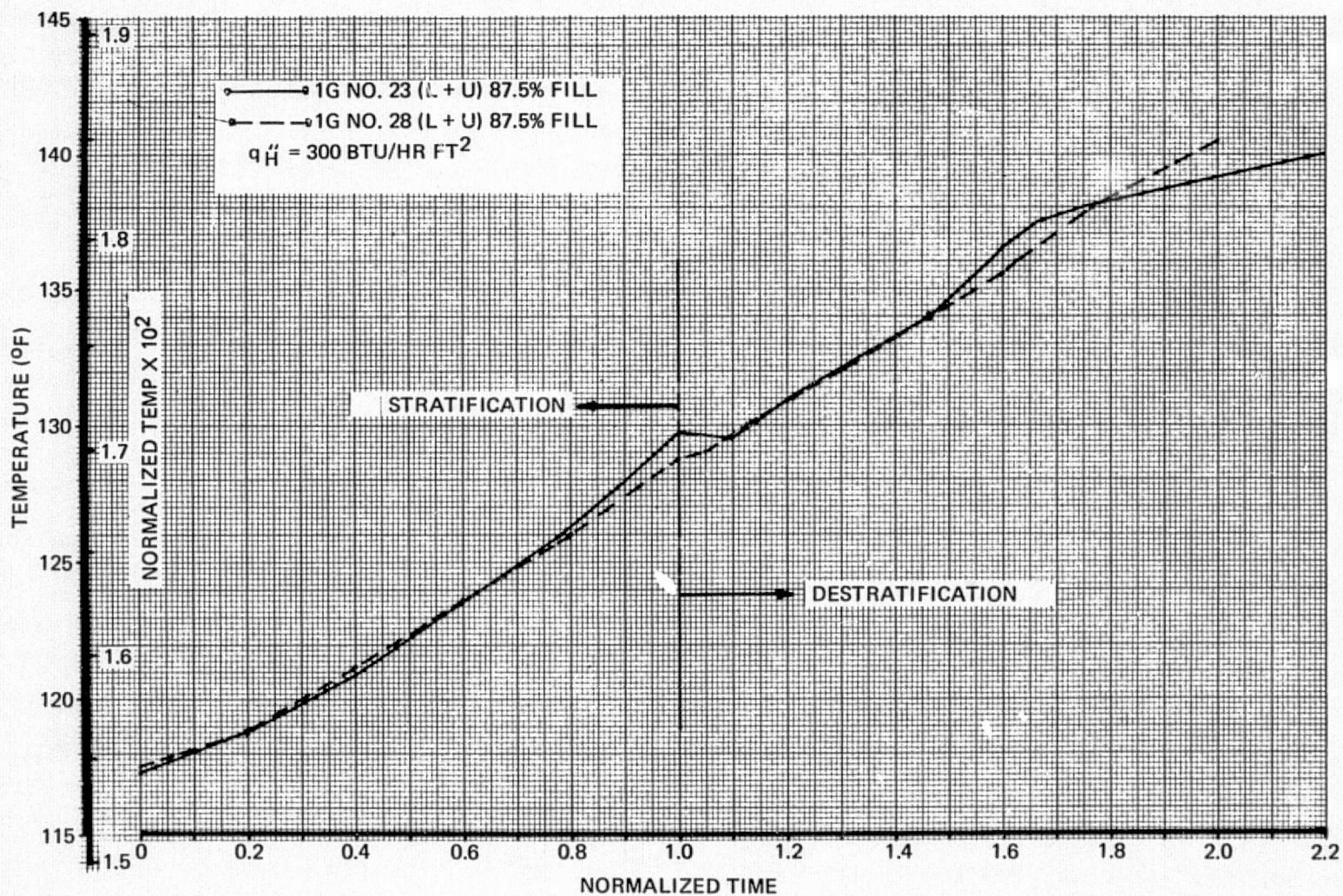




FIGURE 6-44  
REPRODUCIBILITY DATA  
12 IN. TANK - BULK LIQUID TEMP HISTORIES  
TESTS 1G NO. 26 AND NO. 15

140  
135  
130  
125  
120  
115

TEMPERATURE (°F)

1.2  
1.1  
1.0

NORMALIZED TEMP X 10<sup>1</sup>

1G NO. 26 (L) 87.5% FILL  
1G NO. 15 (L) 87.5% FILL  
 $q_H'' = 45 \text{ BTU/HR FT}^2$

STRATIFICATION

DESTRATIFICATION

0 0.2 0.4 0.6 0.8 1.0 1.2 1.4

NORMALIZED TIME

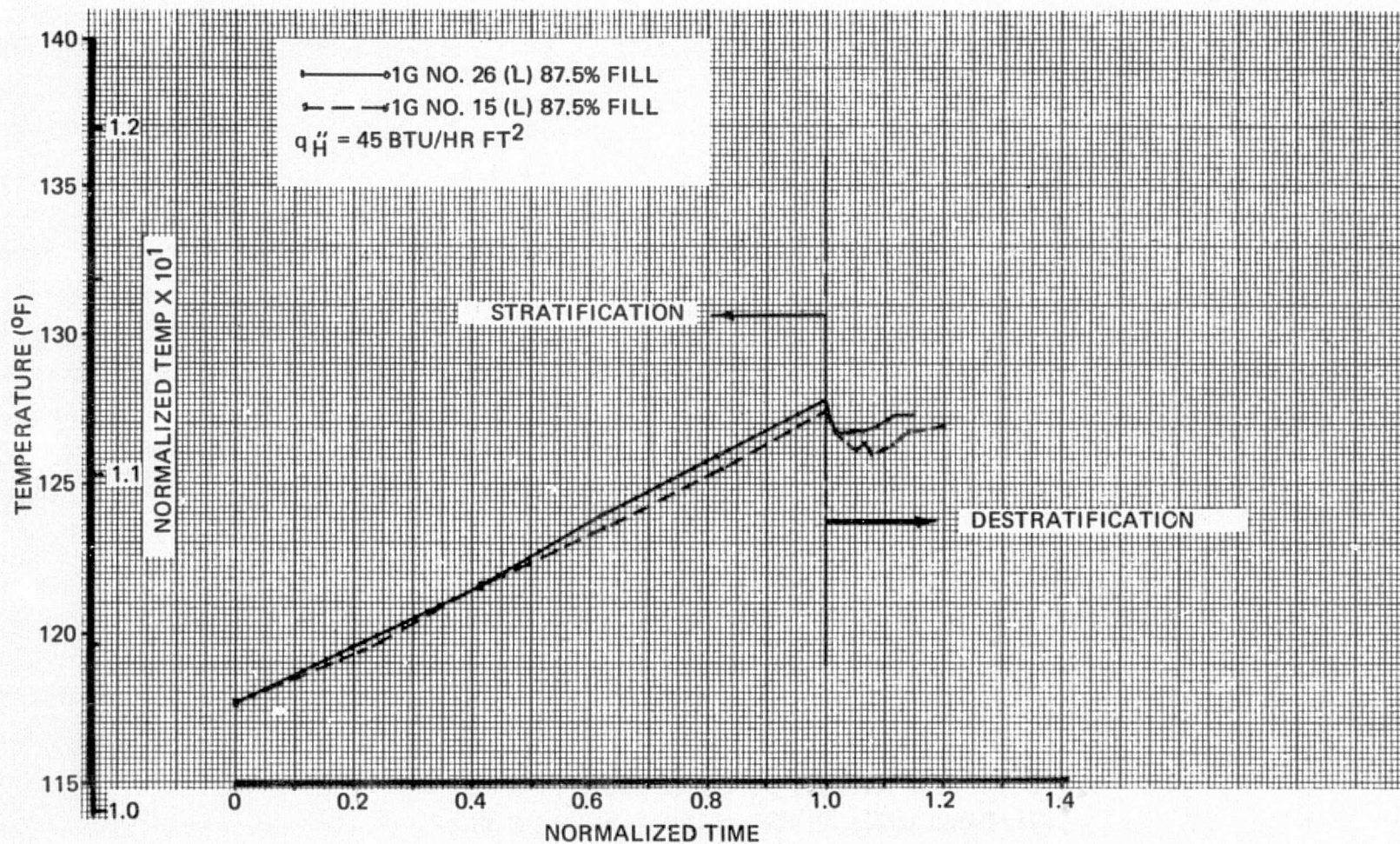


FIGURE 6-45  
REPRODUCIBILITY DATA  
18 IN. TANK - BULK LIQUID TEMP HISTORIES  
TESTS 1G NO. BS AND NO. D

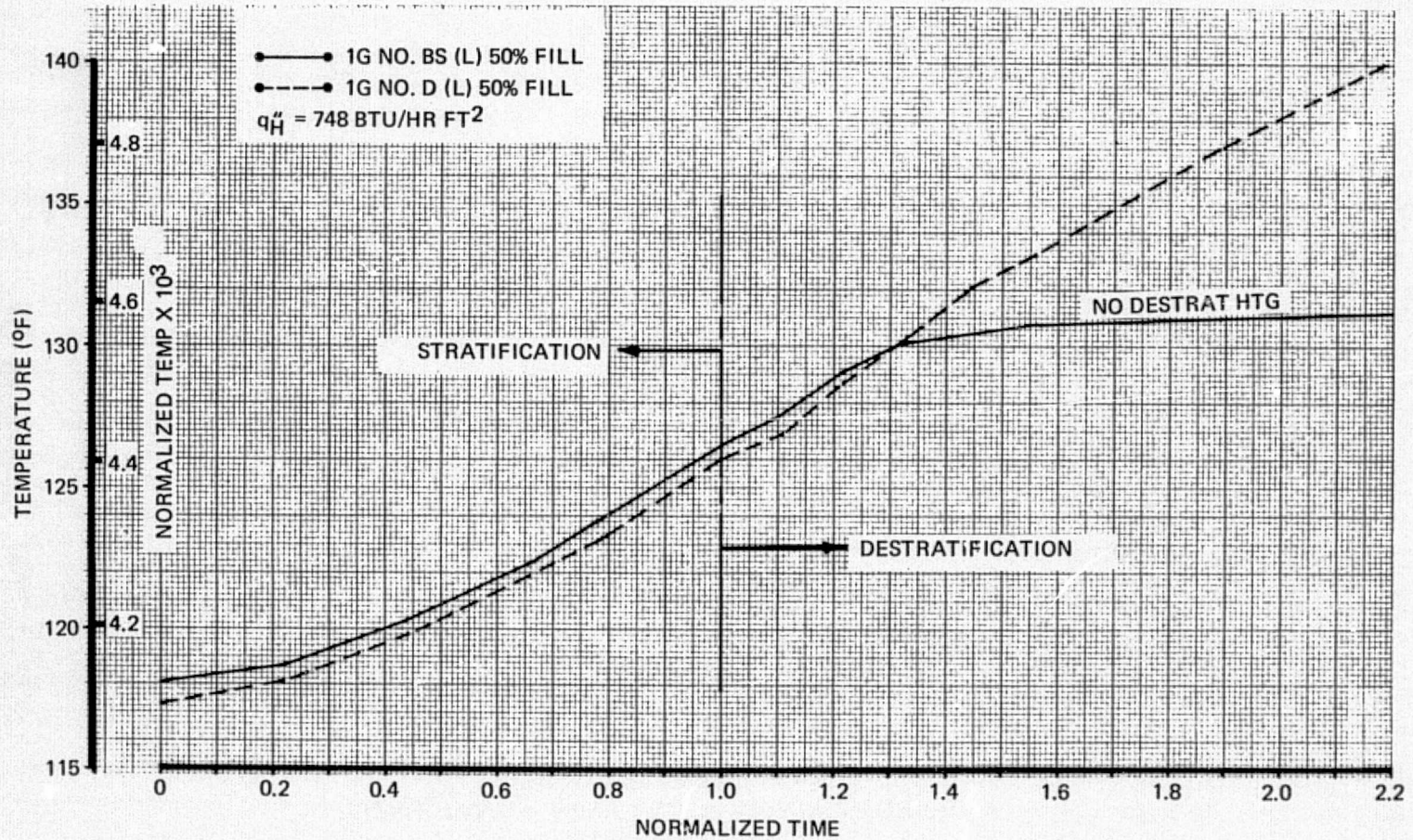


Table 6-2  
LIQUID BULK TEMPERATURE DEVIATION (PERCENT)  
(REPRODUCIBILITY)

6-Inch-Diameter Tank			$Gr_H^*$	$T_b$ Deviation (Percent)
	50% Fill	Liquid Heating	$10^{14}$	0.68
		Liquid-Ullage Heating	$10^{14}$	0.09
	87.5% Fill	Liquid Heating	$7 \times 10^{14}$	0.22
			$10^{15}$	0.13
		Liquid-Ullage Heating	$7 \times 10^{14}$	0.69
			$10^{15}$	0.21
12-Inch-Diameter Tank				
	50% Fill	Liquid Heating	$10^{14}$	0.17
		Liquid-Ullage Heating	$10^{14}$	0.43
	87.5% Fill	Liquid Heating	$10^{14}$	0.3
			$7 \times 10^{14}$	0.35
			$10^{15}$	0.04
		Liquid-Ullage Heating	$7 \times 10^{14}$	1.03
			$10^{15}$	0.18
18-Inch-Diameter Tank				
	50% Fill	Liquid Heating	$10^{15}$	0.21

remain apart over the entire test period. However, in all cases the curves remain nearly parallel emphasizing that the rate of increase of the bulk temperature for each test is nearly identical.

The temperature deviation values are shown to be less than about 1 percent as indicated in Table 6-2. The liquid-bulk temperature represents the integrated value of the respective temperature profile curve and shows that for each repeated test an equal amount of thermal energy has been transferred to the

liquid. It should be noted, however, that for some comparisons, the test conditions for  $\tau > 1.0$  were no longer identical and comparisons made beyond this time have no meaning. This was true since in some tests the heaters were not turned off during the destratification period.

Based upon the reproducibility shown in Figure 6-15 through 6-45 and the deviation values shown in Table 6-2, it is concluded that a high degree of reliability in reproducing the temperature values has been achieved. Thus, these data have demonstrated that each temperature profile "signature," or temperature anomaly, at each respective position has been reliably reproduced for each set of test conditions for each tank. This particular signature trait reproducibility is an important factor in substantiating the data reliability where in a sense every wrinkle in the temperature profile can be repeated for a given tank.

### 6.3 EXPERIMENTAL MODIFIED GRASHOF NUMBER DEFINITIONS

#### 6.3.1 Wall Heat Flux Variation Effects on Modified Grashof Number Definitions

The Modified Grashof number was defined in Section 2 as  $g\beta q'' L^4 / k\nu^2$  where  $q''$  was listed as the wall heat flux. However, during the course of the experimental program, it became necessary to delineate the difference between the heat flux which is generated within the heater blanket,  $q''_H$ , and the heat flux to the liquid,  $q''_l$ . Hence, two different Modified Grashof numbers,  $Gr_H^* (g\beta q''_H L^4 / k\nu^2)$  and  $Gr_l^* (g\beta q''_l L^4 / k\nu^2)$ , are used in discussing the data. The experimental value of  $Gr_H^*$  for any test is constant with time since  $q''_H$  is kept constant. However  $Gr_l^*$  varies with time since  $q''_l$  will differ from  $q''_H$  by the rate of energy storage in the tank walls and the heater blanket. In fact, both  $Gr_l^*$  and the Interface number  $(h_{fg} k_l / q''_l Dc_{p_l})$  change by more than an order of magnitude between  $\tau = 0$  and  $\tau = 1.0$ .

The term  $Gr_H^*$  is the scaling term which must be used when treating the total tank system. Here, the tank walls, the insulation, and the heaters, in addition to the liquid and ullage, make up the total system. Since the three tanks are scaled thermodynamically and geometrically and have identical material, it is



only necessary that  $Gr_H^*$  which reflects the boundary heating condition be the same for each tank. When this dimensionless group is kept the same for two separate tanks along with the Fourier and Interface numbers, then the two tanks are considered scaled to one another.

It is important to realize, however, that if the liquid and ullage are treated as the thermodynamic system, that  $Gr_\ell^*$  and not  $Gr_H^*$  will have meaning with respect to this system. This can be explained by examining the equation

$$q_H'' = q_\ell'' + q_s'' \quad (6-3)$$

where  $q_H''$  equals the total heat-flux output from the electrical heater blankets,  $q_\ell''$  equals the heat-flux transferred to the liquid at any time,  $t$ , and  $q_s''$  equals the instantaneous rate of accumulation or storage of thermal energy per unit area of tank wall, insulation, and heaters. Since  $q_\ell''$  depends on the tank walls having an inside surface temperature greater than that of the contained fluid, the major portion of  $q_H''$  in the early part of the test period will be accounted for by  $q_s''$ .

Figures 6-46 and 6-47 are typical examples of the trend of the measured values of  $Gr_\ell^*$  with respect to  $Gr_H^*$  as a function of time for this study. As can be observed, the ratios of  $Gr_\ell^*/Gr_H^*$  (which is also equal to  $q_\ell''/q_H''$ ) are less than one over the test period although their values are increasing with time. It is likely that this ratio will eventually reach a constant value, but the data are insufficient to show this value. Figures 6-48 through 6-51 show typical curves of  $Gr_H^*$  and  $Gr_\ell^*$ . It should be noted that the value of  $Gr_H^*$  in these figures increases slightly with time even though  $q_H''$  is kept constant. This change reflects the liquid property changes with temperature that occur during the course of a test. However, the initial value of  $Gr_H^*$  (i. e., at  $\tau=0.0$ ) is the one referred to in this report. The  $Gr_H^*$  and  $Gr_\ell^*$  values at  $\tau=1.0$  for each test are shown in Appendix A. Volume II of this final report includes the  $Gr_H^*$  and  $Gr_\ell^*$  curves as a function of the normalized time for each experiment.

In summary, there are three main points that have been made. These are:

- A. The independent scaling parameter  $Gr_H^*$  is the proper Modified Grashof number for scaling a tank system.

## FRACTION OF HEAT TRANSFERRED TO LIQUID STRATIFICATION TESTS

FIGURES 6-46 AND 6-47

### NOMENCLATURE

$Gr^*$ . . . .	Modified Grashof number
$q''_H$ . . . .	Measured heater heat flux at source
$q''_l$ . . . .	Determined liquid heat flux, experimentally absorbed
(L+U) . . . .	Liquid and ullage heating
(L) . . . . .	Liquid heating

FIGURE 6-46  
FRACTION OF HEAT TRANSFERRED TO LIQUID-STRATIFICATION TESTS

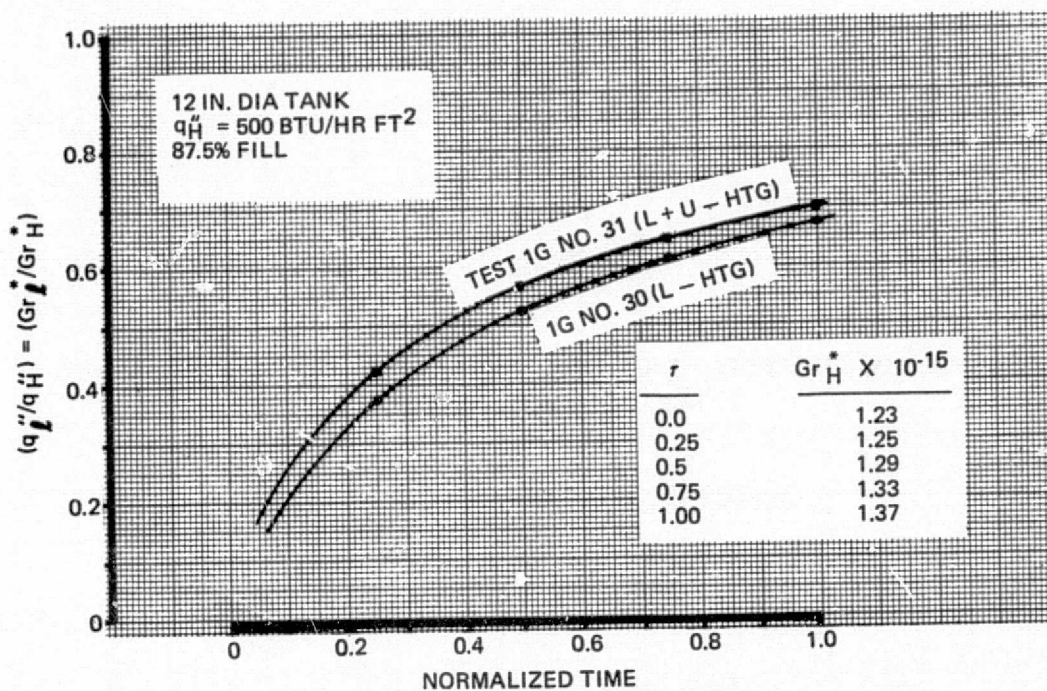


FIGURE 6-47  
FRACTION OF HEAT TRANSFERRED TO LIQUID-STRATIFICATION TESTS

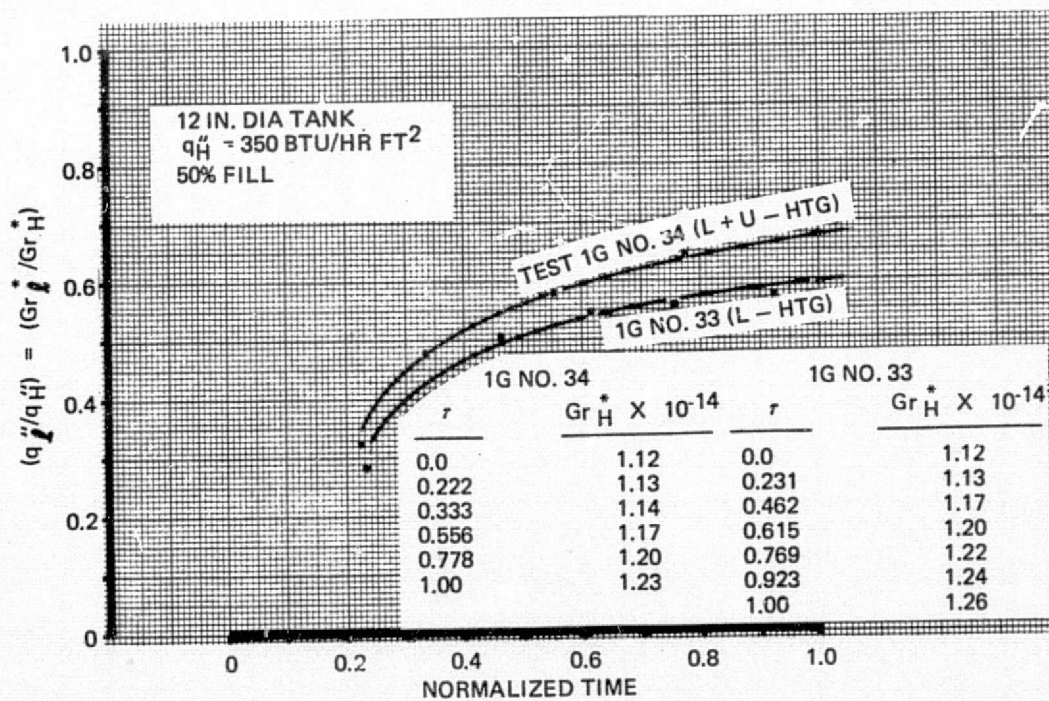


FIGURE 6-46  
FRACTION OF HEAT TRANSFERRED TO LIQUID-STRATIFICATION TESTS

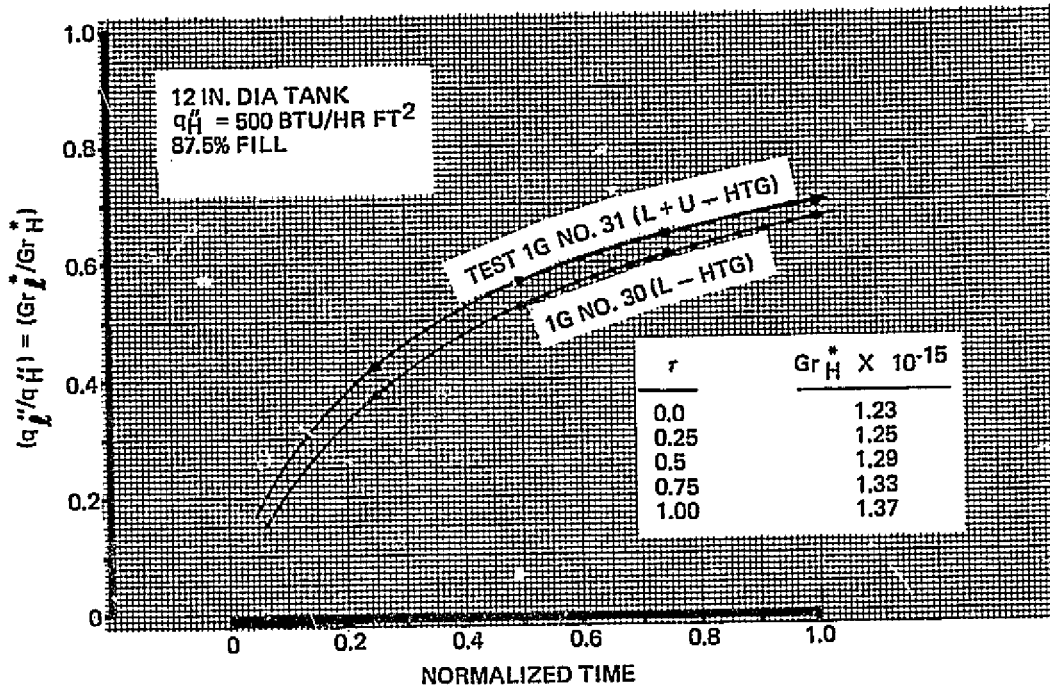
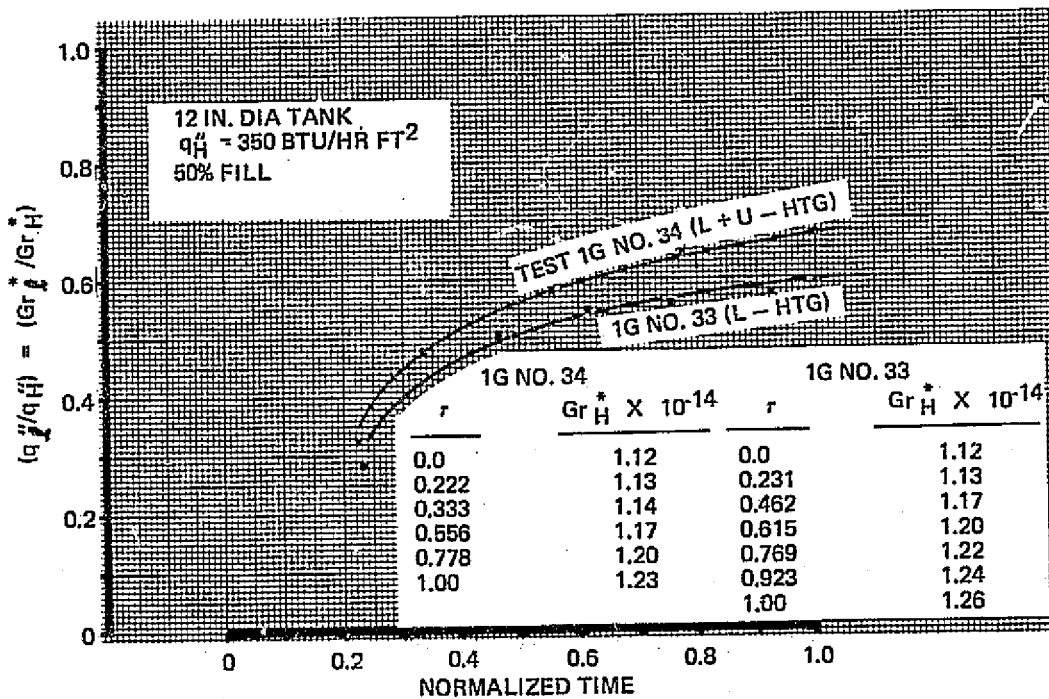


FIGURE 6-47  
FRACTION OF HEAT TRANSFERRED TO LIQUID-STRATIFICATION TESTS





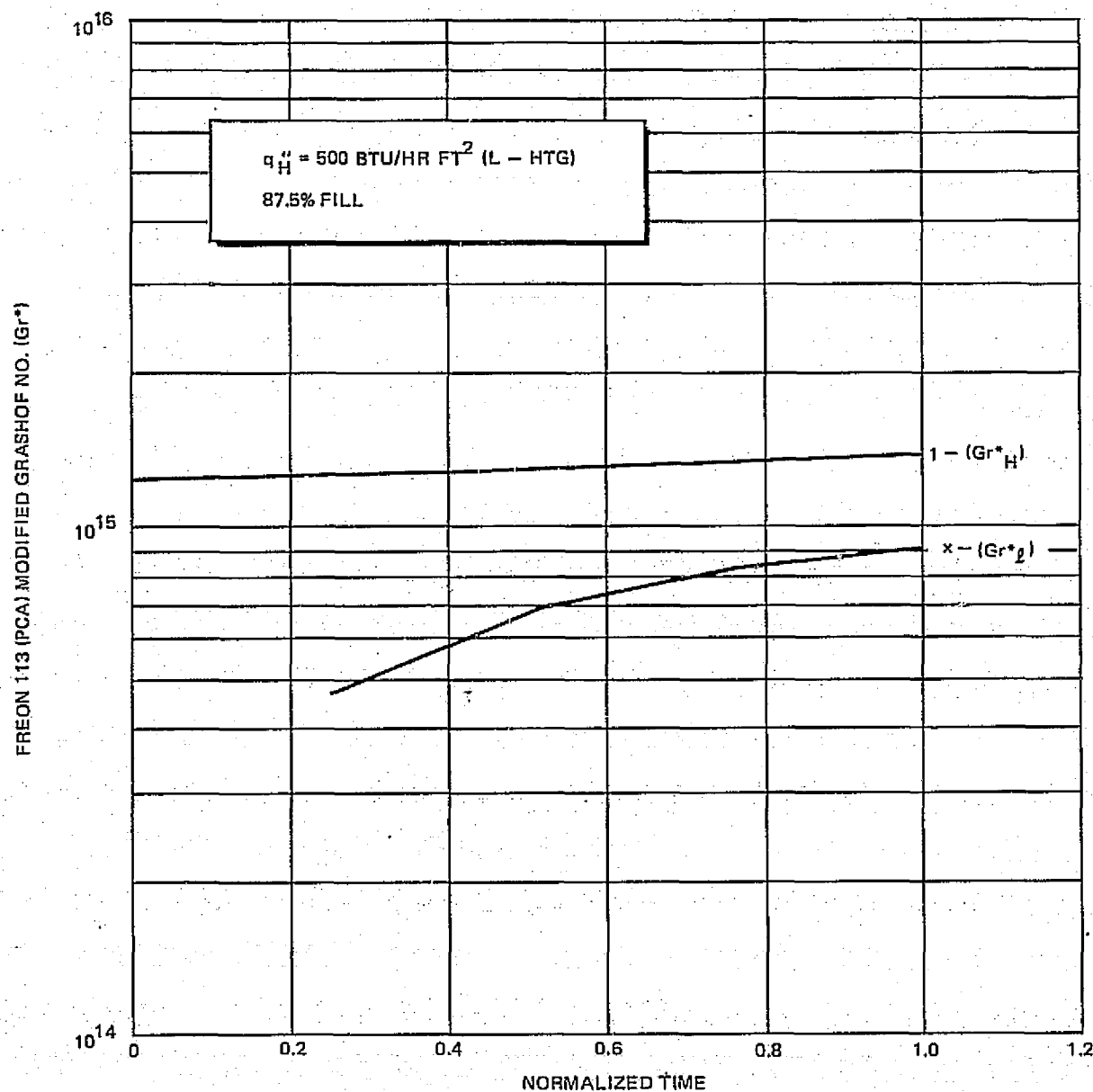
LIQUID MODIFIED-GRASHOF NUMBER HISTORY CURVES  
STRATIFICATION TESTS

FIGURES 6-48 THROUGH 6-51

NOMENCLATURE

- $\beta$  . . . Coefficient of thermal expansion of fluid
- $\rho$  . . . Fluid density
- $\mu$  . . . Fluid viscosity
- $k$  . . . Fluid thermal conductivity
- $T$  . . . Fluid temperature

FIGURE 6-48  
12 IN. TANK 1G NO. 30 LIQUID MODIFIED GRASHOF NO. HISTORIES-STRAT



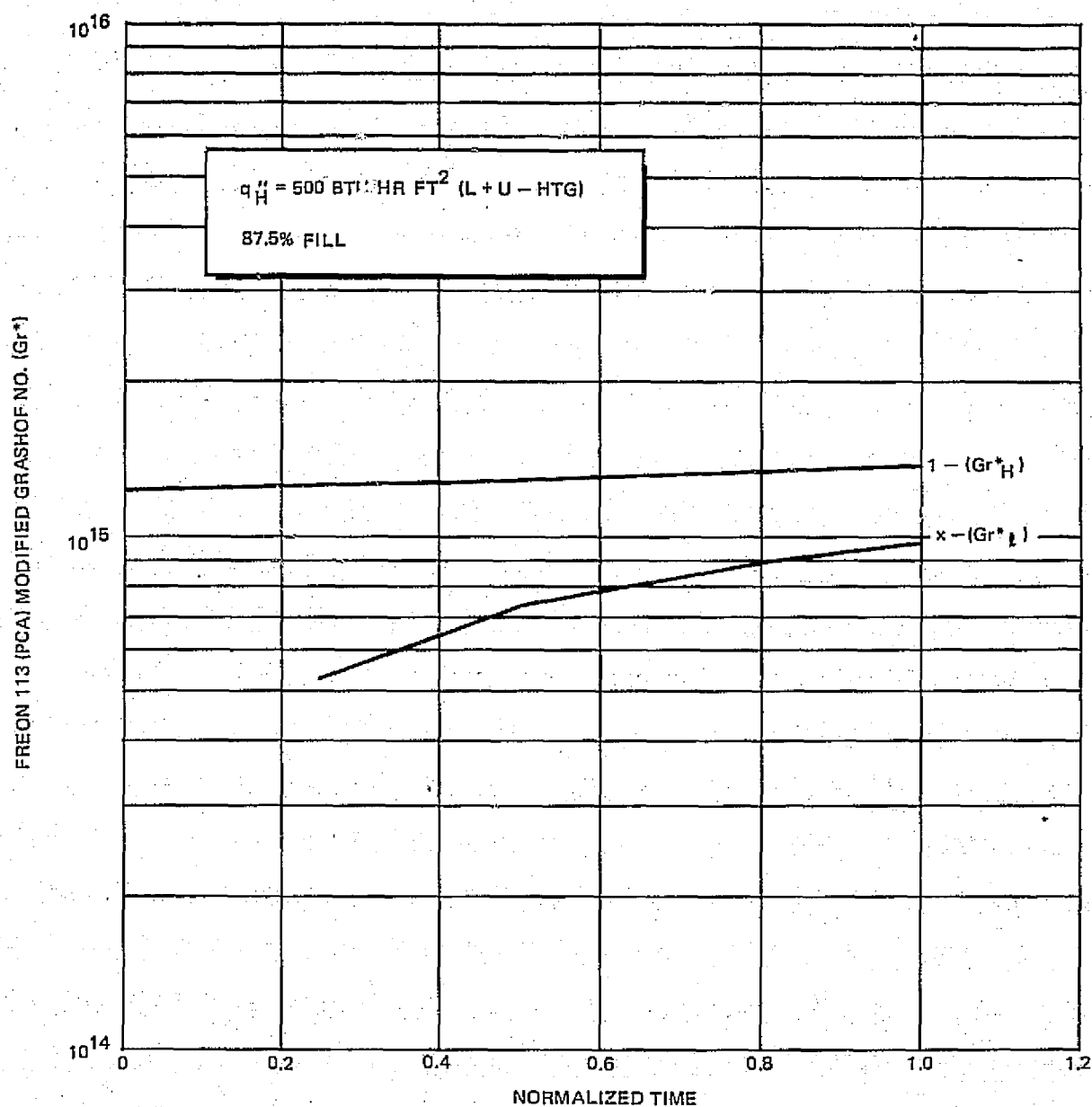
$$Gr^* = \frac{9g\beta L^3}{(\mu/\rho)^2} \left( \frac{q'' L}{k} \right)$$

L = FLUID DEPTH

1 = BASED ON  $q_H''$  WATTAGE MEASURED INPUT

x = BASED ON EXPERIMENTALLY DETERMINED;  $q_L''$

FIGURE 6-49  
12 IN. TANK 1G NO. 31 LIQUID MODIFIED GRASHOF NO. HISTORIES-STRAT



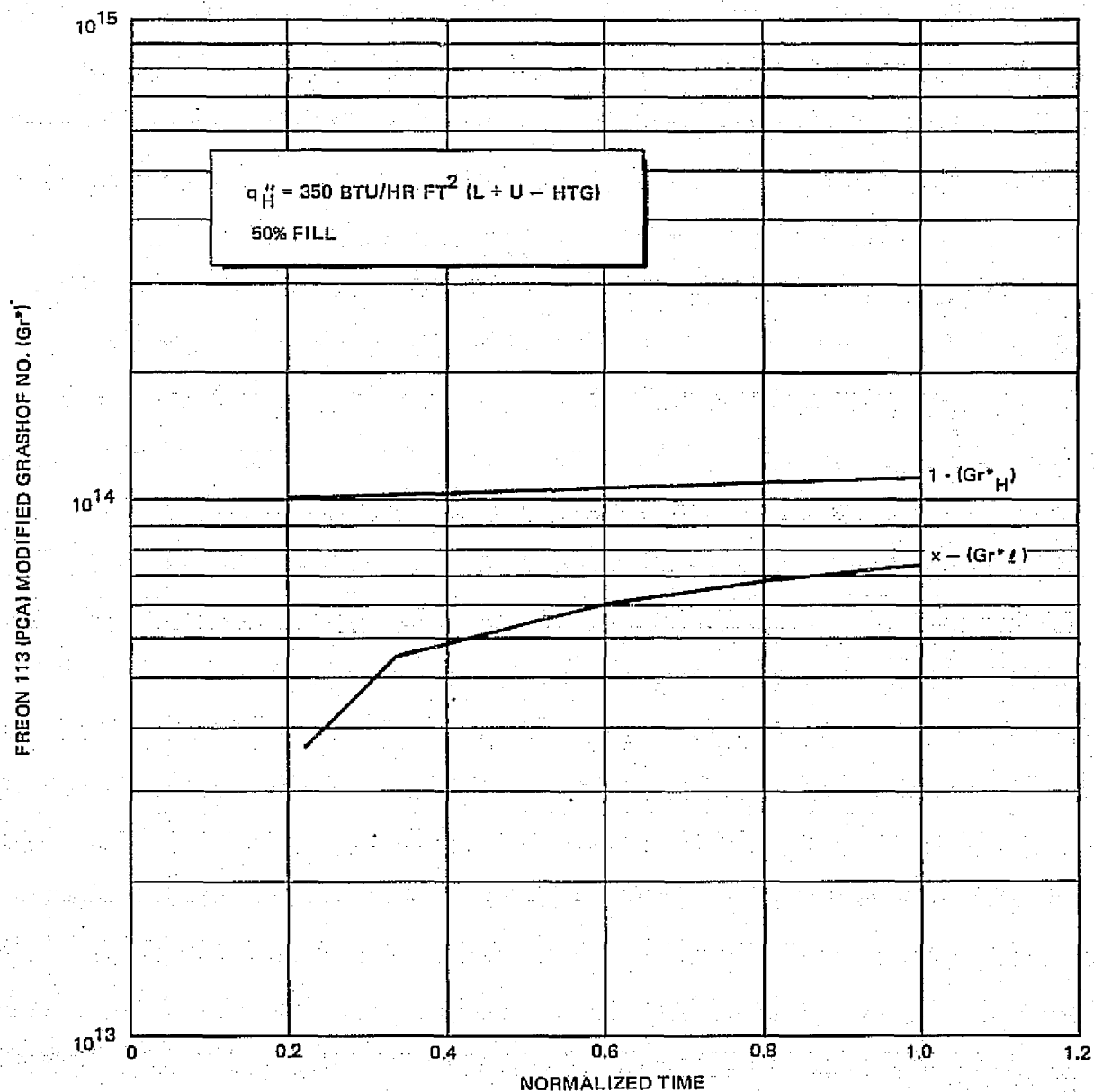
$$Gr^* = \frac{g \beta L^3}{(\mu/\rho)^2} \left( \frac{q'' L}{k} \right)$$

L = FLUID DEPTH

1 = BASED ON  $q_H''$  WATTAGE MEASURED INPUT

x = BASED ON EXPERIMENTALLY DETERMINED;  $q_L''$

FIGURE 6-50  
12 IN. TANK 1G NO. 34 LIQUID MODIFIED GRASHOF NO. HISTORIES-STRAT



$$Gr^* = \frac{g \beta L^3}{(\mu/\rho)^2} \left( \frac{q'' L}{k} \right)$$

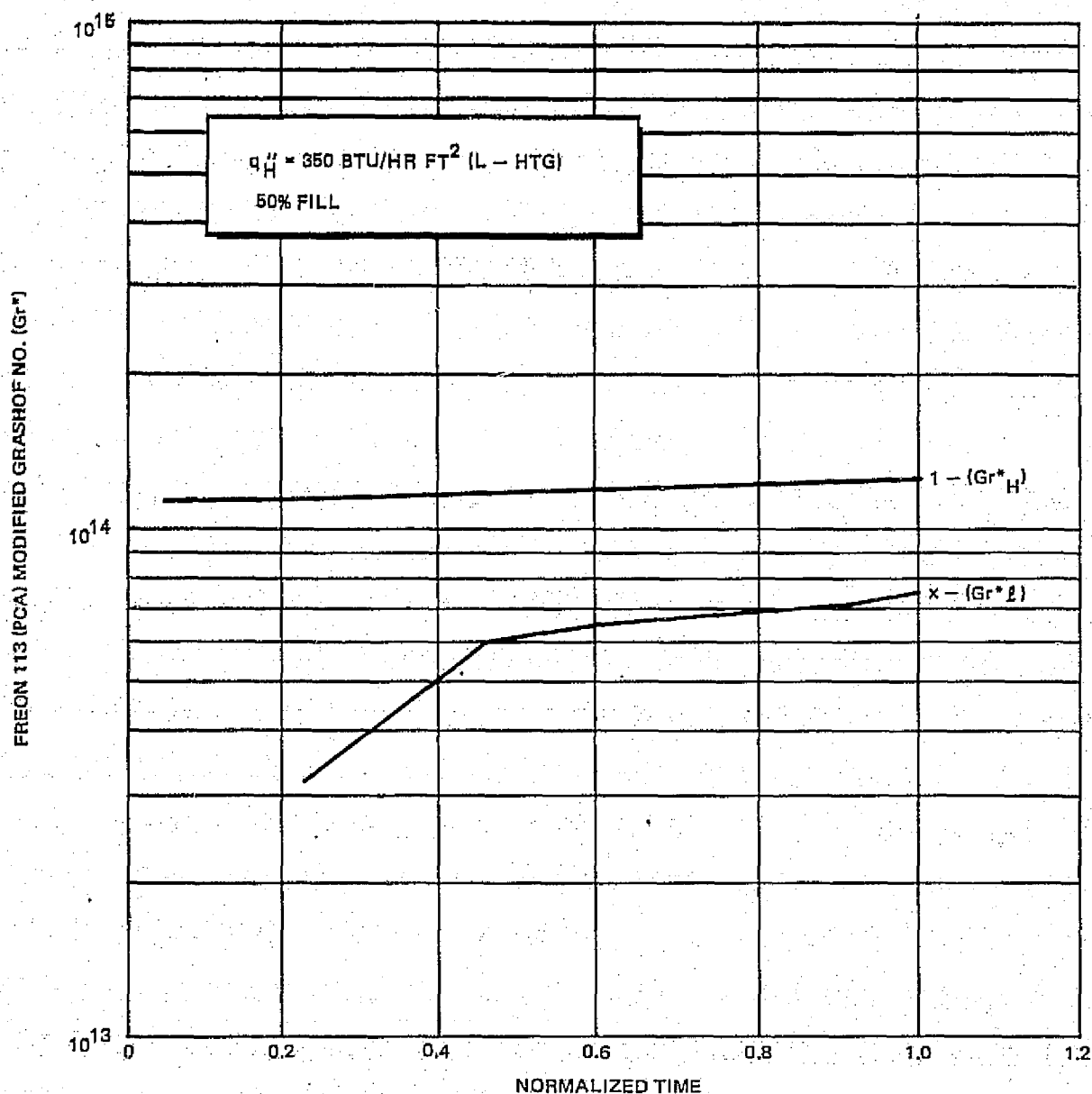
$L$  = FLUID DEPTH

1 — THEORETICALLY BASED ON MEASURED  $q_H''$  WATTAGE INPUT

x — EXPERIMENTALLY BASED ON DETERMINED  $q_L''$



FIGURE 6-51  
12 IN. TANK 1G NO. 33 LIQUID MODIFIED GRASHOF NO. HISTORIES-STRAT



$$Gr^* = \frac{g \beta L^3}{(\mu/\rho)^2} \left( \frac{q'' L}{k} \right)$$

L = FLUID DEPTH

1 - THEORETICAL BASED ON MEASURED  $q_H''$  WATTAGE INPUT  
x - EXPERIMENTAL BASED ON MEASURED  $q_L''$

- B. The Modified Grashof number,  $Gr_l^*$ , is a dependent parameter obtained experimentally, that might be useful when fluid and ullage are considered as a system.
- C. The value of  $Gr_l^*$  will range from zero to a value less than  $Gr_H^*$  during the stratification period.

#### 6.4 CRITERIA FOR GAGING DEGREE OF SCALING

The following subsections compare the dimensionless pressure and dimensionless temperature data for scaled tests. For such scaled tests, the  $Gr_H^*$ ,  $Fo$ , and  $I$  are equal for the two tanks. Hence, for percent scaling it would be expected that the dimensionless pressure and temperature values be the same for these scaled tests. However, no established criteria to measure the degree of success in scaling are available. Thus, the criteria used here were selected to represent both the integrated or volumetric heat transfer effect as well as a pointwise effect. The requirement that the bulk temperatures

$$\bar{T}_{bA}(\tau) = \bar{T}_{bB}(\tau) \quad (6-4)$$

is at best a necessary requirement for scaling and reflects the integrated heat transfer effect. On the other hand, the temperature profile requirement at a point

$$\bar{T}_A(\bar{x}, \bar{y}, \bar{z}, \tau) = \bar{T}_B(\bar{x}, \bar{y}, \bar{z}, \tau) \quad (6-5)$$

if met everywhere in both liquid and the ullage would likely provide a necessary and sufficient condition for complete scaling. The pressure requirement

$$\bar{P}_A(\tau) = \bar{P}_B(\tau) \quad (6-6)$$

may lie somewhere in between the above two criteria because in effect it is an integrated value and yet is coupled to the liquid surface temperature. The extent to which these three conditions are met will characterize the degree of scaling that was accomplished in two scaled tank tests.

A quantitative guide for the degree of scaling can probably best be considered in terms of the percent deviation between the values of  $\bar{p}$ ,  $\bar{T}_b$ , and  $\bar{T}$  in a set of scaled tests. The percent deviation is presented for each term,  $\bar{p}$ ,  $\bar{T}_b$ , and  $\bar{T}$ , in Subsections 6.5 and 6.6.

## 6.5 PRESSURE HISTORY SCALING RESULTS

### 6.5.1 Introduction

The pressure history scaling curves are plotted in both the dimensional pressure,  $p$ , and the dimensionless pressure,  $\bar{p}$ , on the same graph. This can be done since  $p$  and  $\bar{p}$  only differ by the constant  $(q_H'' \theta/D)$  which is divided into  $p$  to obtain  $\bar{p}$ . This term is constant for any two scaled tests using the same liquid. Pressure measurements were obtained both with a pressure transducer and a pressure gage. Subsequent calculations used the arithmetic average of these two experimental pressure values. However, only the pressure transducer was used in the high-g tests.

The stratification portion of each experiment corresponds to values of  $\tau$  less than or equal to 1.0. All scaled tests considered here, with liquid heating only, were scaled reasonably well in this regime. The liquid-ullage heating tests did not compare as favorably.

### 6.5.2 Scaling Evaluation

Figures 6-52 through 6-61 show the pressure as a function of time for sets of scaled tests covering the range of tank configurations discussed earlier. The most general observation that can be made is that the matched sets of curves agree well for liquid-only heating while the agreement is not as good for the liquid and ullage heating cases. The extent to which scaling was achieved may be judged on the basis that the dimensionless pressure curves definitely indicate the same general trends and values. This should be judged taking into account that the two tanks may have different operating conditions. As an example, when the 6-inch tank experiences 27 g's with 2,230 Btu/hr-ft<sup>2</sup>, the scaled equivalent is an 18-inch tank at 1 g with 748 Btu/hr-ft<sup>2</sup>. Thus, when the dimensionless pressure curves agree reasonably well with entirely different operating conditions, it is likely a result of scaling.

One method of comparison uses the pressure difference values between  $\tau = 0$  and  $\tau = 1.0$ . Here, the rise in pressure for one tank is compared with that of

# SCALING PRESSURE DATA TANK-ULLAGE-PRESSURE HISTORIES

FIGURES 6-52 THROUGH 6-61

## NOMENCLATURE

$q''_H$	.....	Measured heater heat-flux source, Btu/hr-ft <sup>2</sup>
$\theta$	.....	Stratification test period
$D$	.....	Tank diameter
$Gr_H^*$	.....	Modified Grashof number based upon $q''_H$
CHPRESS	...	Characteristic pressure, $(q''_H \theta / D)$
$p$	.....	Tank-ullage measured pressure
$\bar{p}$	.....	Normalized pressure, $(p/CHPRESS)$
6 in. -8G#2S	.	Test title (e. g., 6-inch dia tank - 8 g's test number 2; S indicates no heating during destratification testing)



FIGURE 6-52  
SCALING PRESSURE DATA - TANK PRESSURE HISTORY,  
6 IN. 8G2 - 12 IN. 1G30

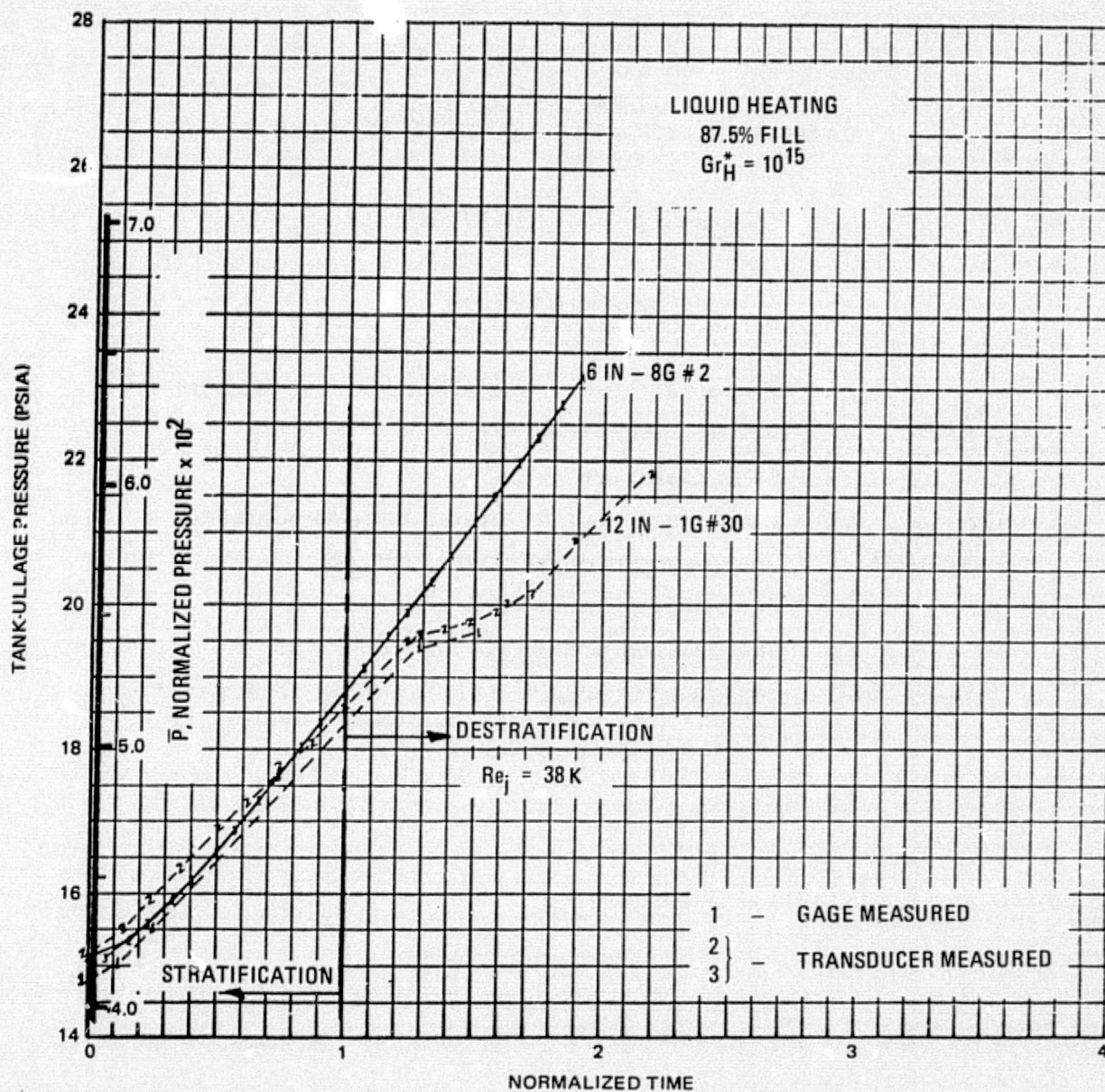


FIGURE 6-53  
SCALING PRESSURE DATA – TANK PRESSURE HISTORY,  
6 IN. 8G9S – 12 IN. 1G33

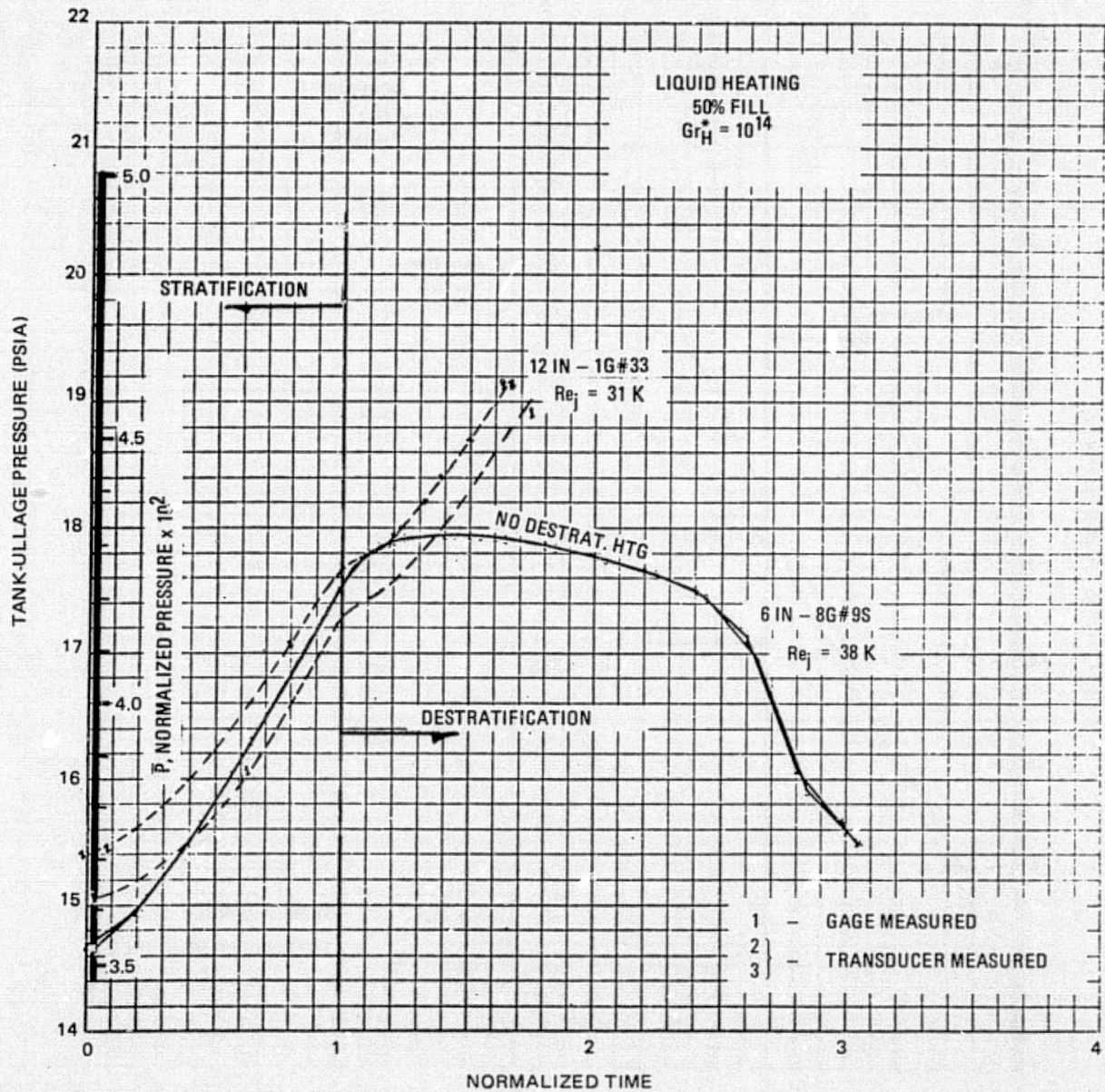




FIGURE 6-54  
SCALING PRESSURE DATA – TANK PRESSURE HISTORY,  
6 IN. 8G1 – 12 IN. 1G20

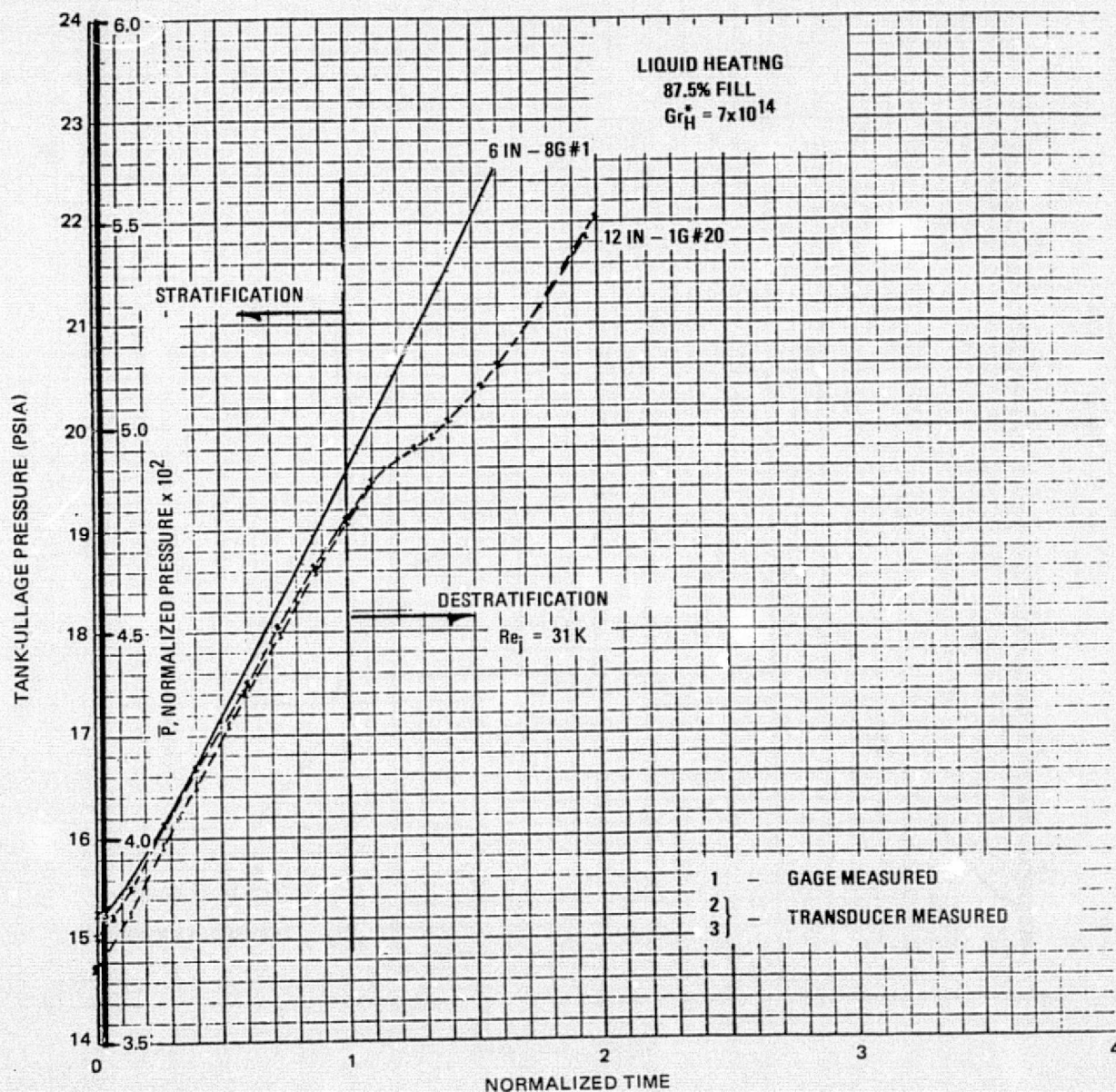


FIGURE 6-55  
SCALING PRESSURE DATA – TANK PRESSURE HISTORY,  
6 IN. 27G1S – 18 IN. 1GBS

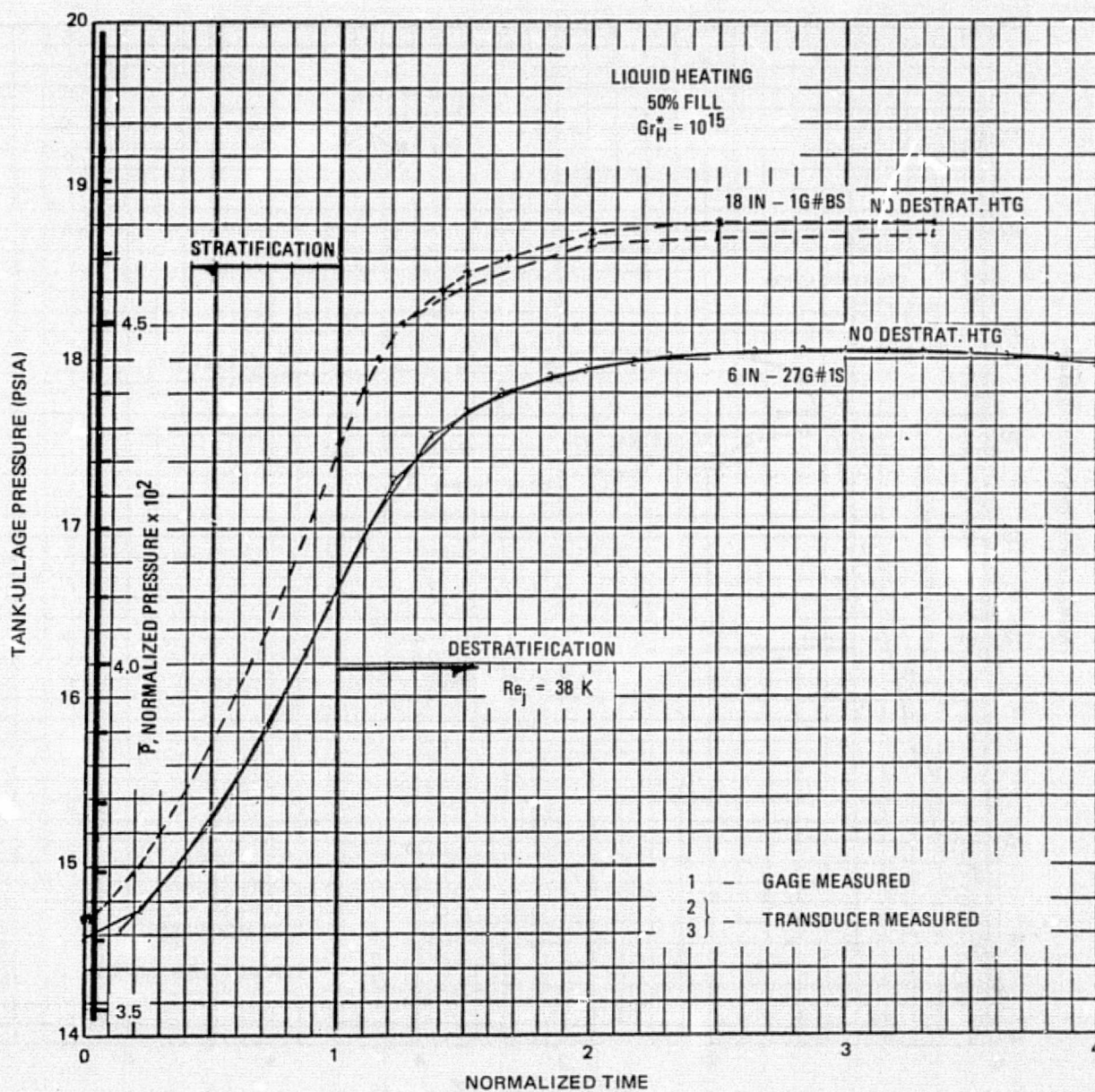




FIGURE 6-56  
SCALING PRESSURE DATA – TANK PRESSURE HISTORY,  
6 IN. 27G3S – 18 IN. 1G1S

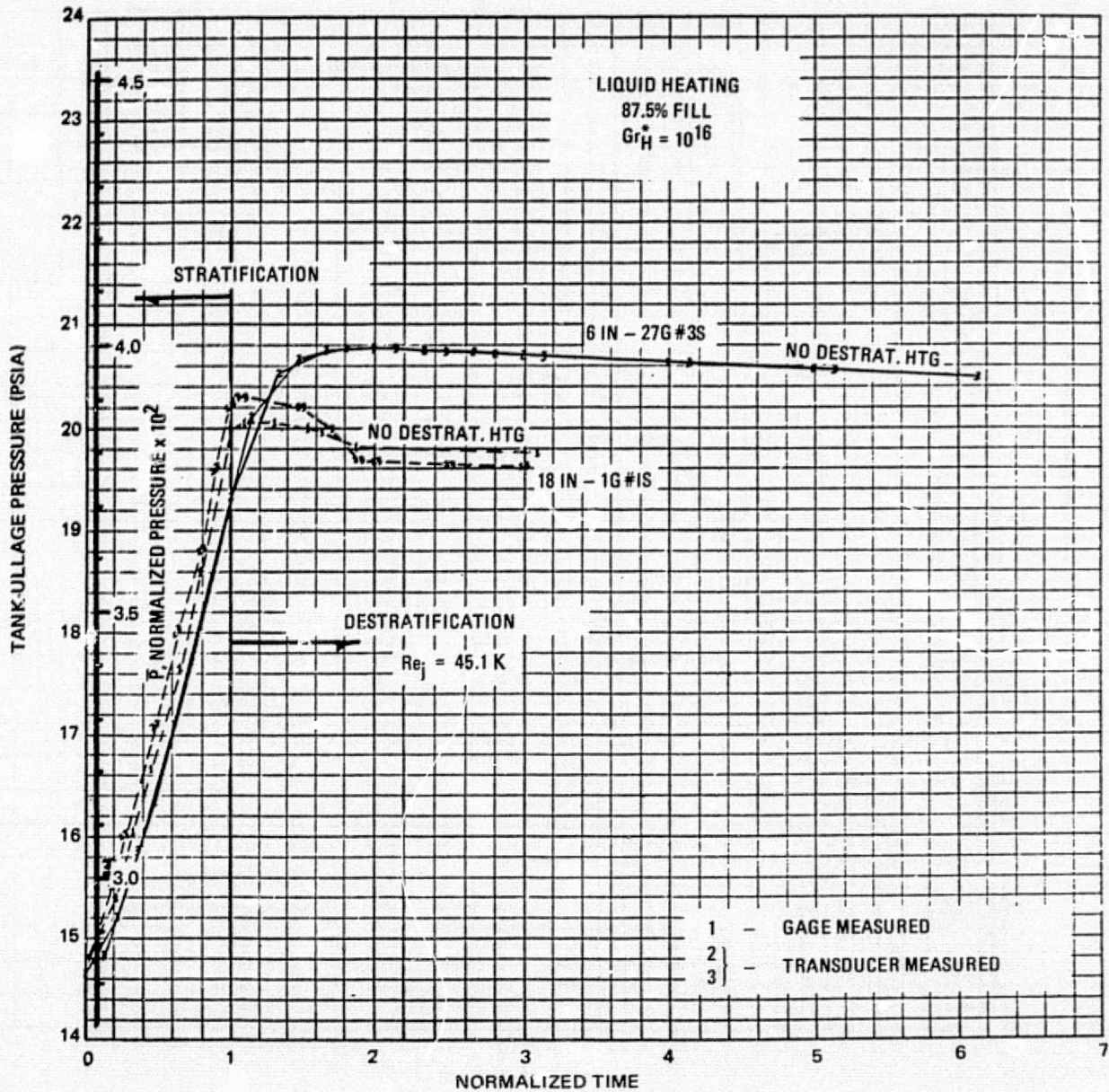


FIGURE 6-57  
SCALING PRESSURE DATA – TANK PRESSURE HISTORY,  
6 IN. 8G14 – 12 IN. 1G26 AND 15

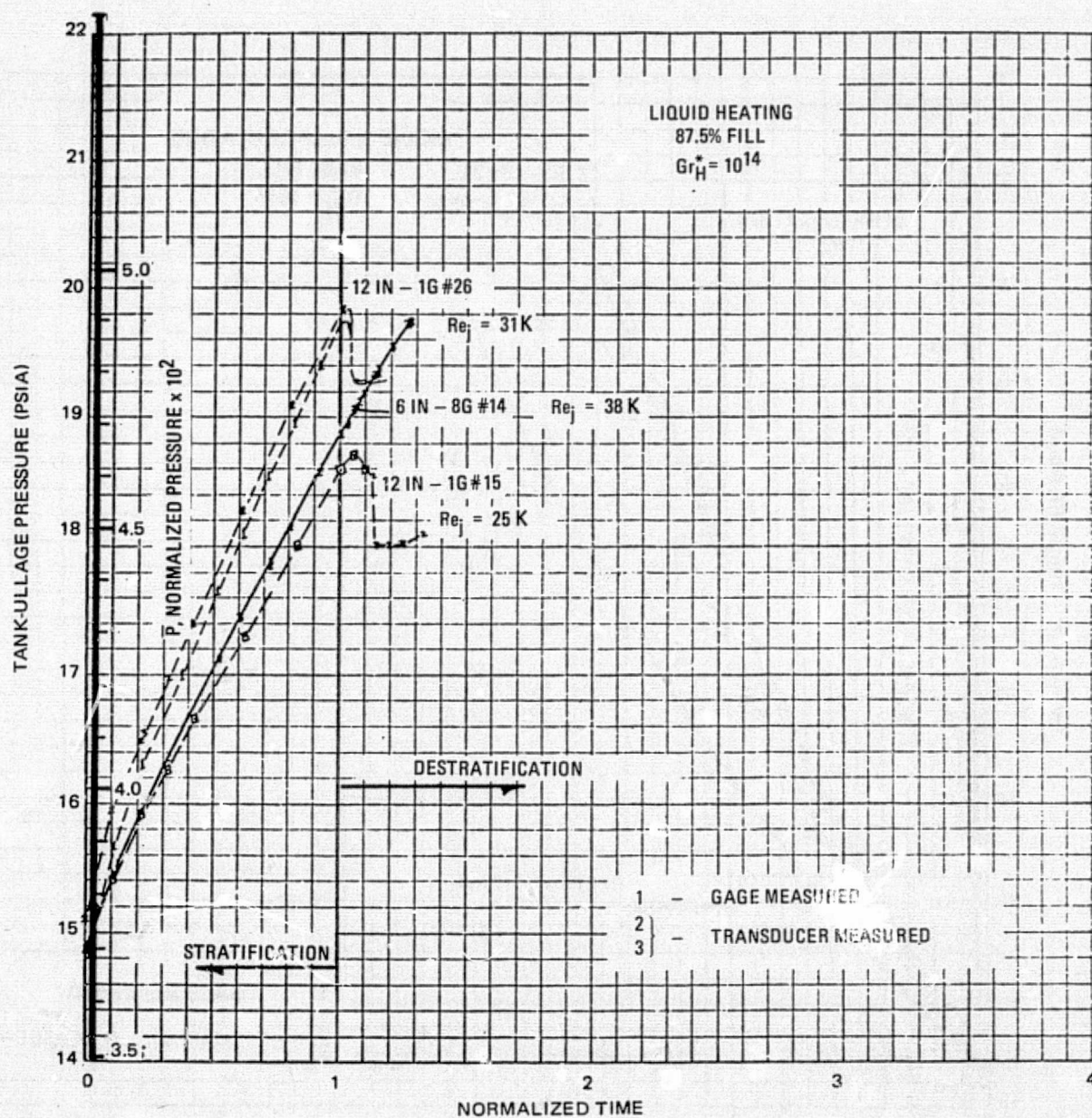




FIGURE 6-58  
SCALING PRESSURE DATA – TANK PRESSURE HISTORY,  
6 IN. 8G3 – 12 IN. 1G31 AND 17

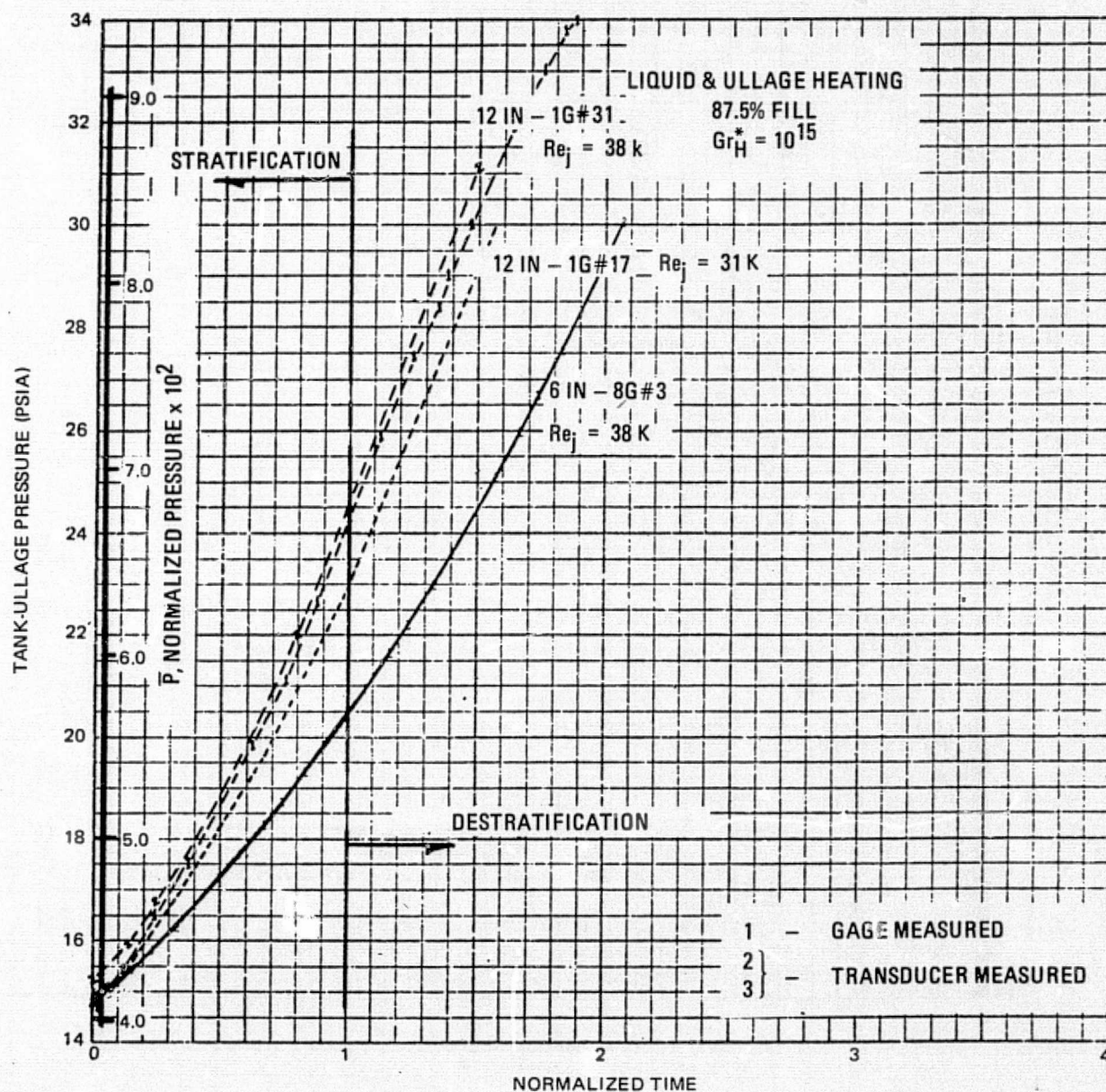


FIGURE 6-59  
SCALING PRESSURE DATA - TANK PRESSURE HISTORY,  
6 IN. 8G10S AND 16S - 12 IN. 1G34

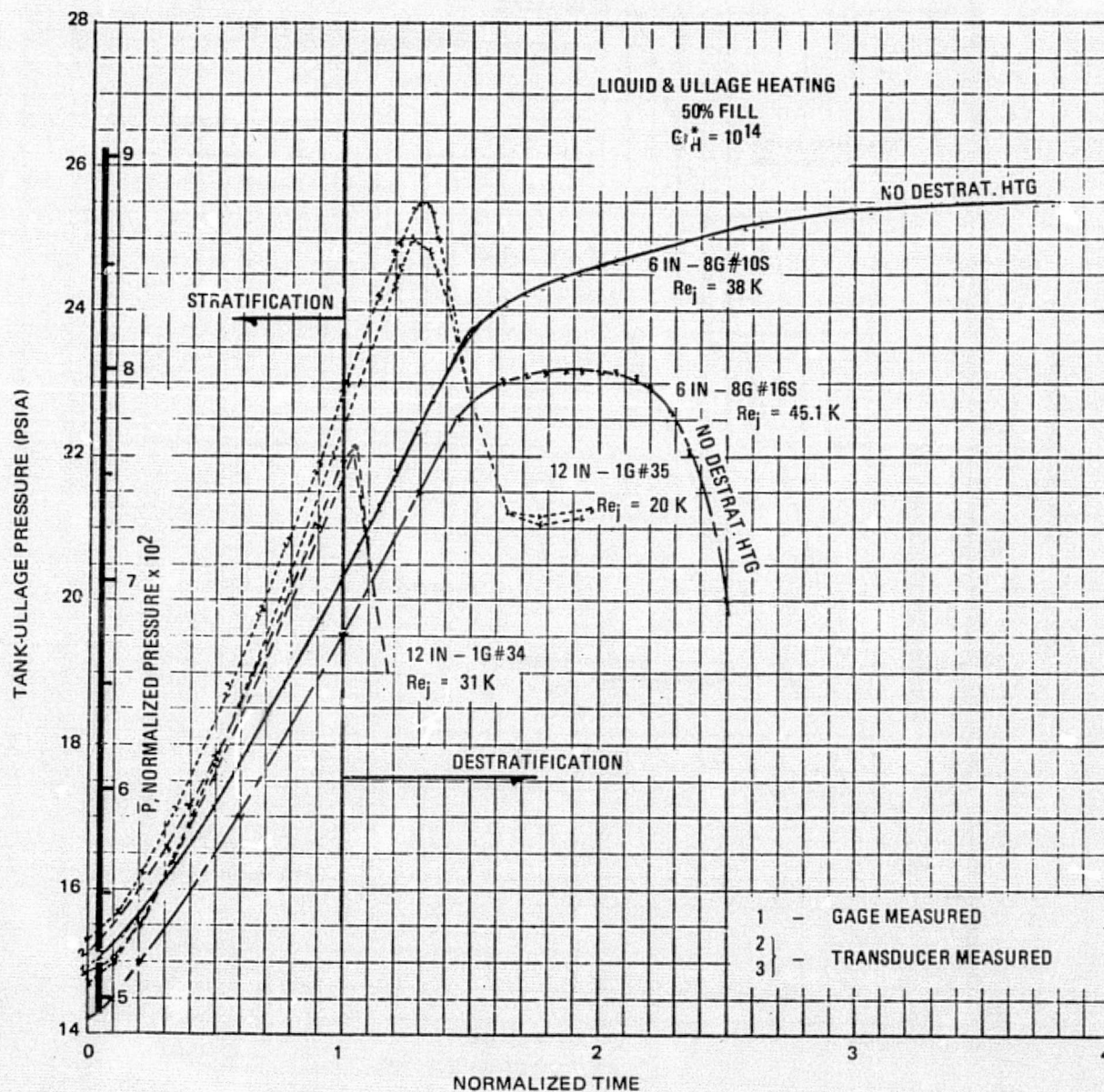




FIGURE 6-60  
SCALING PRESSURE DATA – TANK PRESSURE HISTORY,  
6 IN. 8G4 AND 35 – 12 IN. 1G23

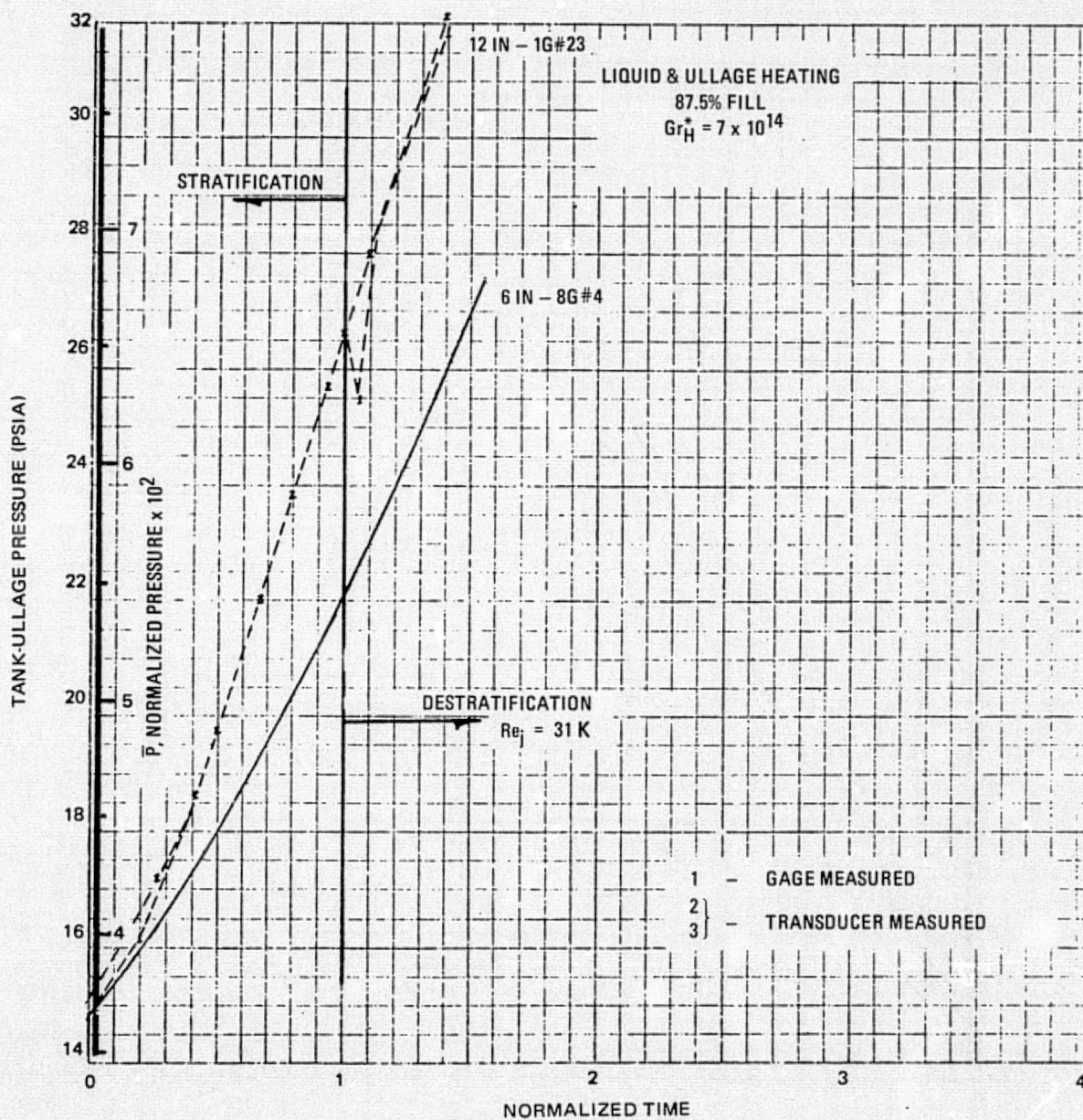
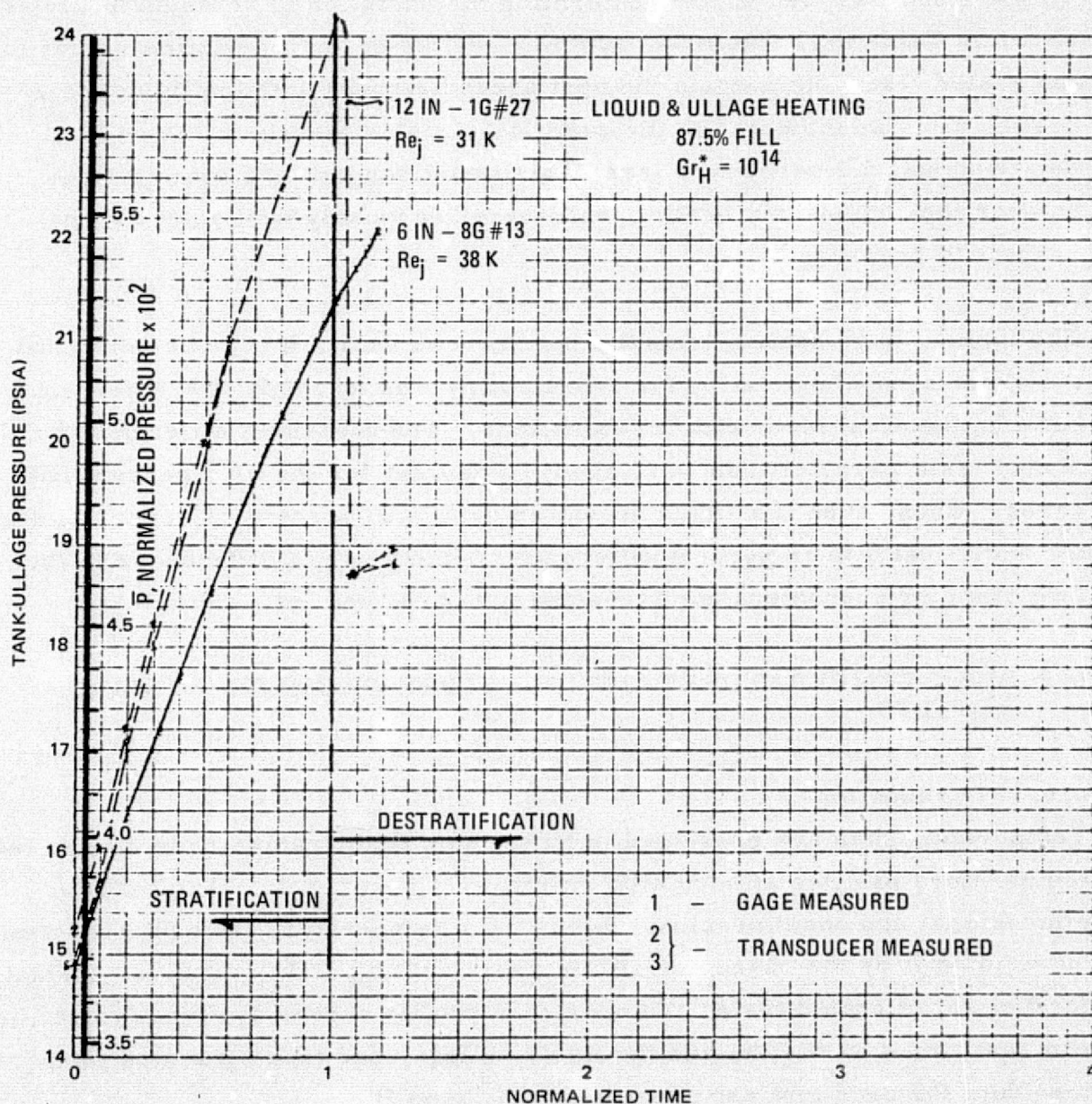


FIGURE 6-61  
SCALING PRESSURE DATA – TANK PRESSURE HISTORY,  
6 IN. 8G13 – 12 IN. 1G27



the other scaled tank and a percent difference is obtained by dividing this difference by the average initial pressure of both tanks, i.e.,

$$\frac{\Delta p_{1-2}}{p_{i,avg}} = \left| \frac{p_{1f} - p_{1i}}{1/2 (p_{1i} + p_{2i})} - \frac{p_{2f} - p_{2i}}{1/2 (p_{1i} + p_{2i})} \right| \quad (6-7)$$

This method was also used to determine the deviation in reproducibility as shown in Table 6-1. Table 6-3 summarizes the percent deviation values for the scaled tests. Here again the best agreement was with the liquid-only heating tests as indicated in the qualitative evaluation where the percent deviation was 5.1 percent or less. This would suggest in a quantitative manner that liquid-only heating tests were reasonably well scaled with respect to pressure.

The liquid-ullage heating tests did not scale as well. It is to be noted that the error band when testing for repeatability was up to about 8.4 percent between identical tests with the same tank. The measured difference for the scaled tests were between 16 to about 28 percent for the 87.5 percent fill cases. Thus, even if a likely spread in data of 10 percent is accounted for, the additional 6 to 18 percent difference is likely due to differences in the heat transfer phenomena not accounted for in the scaling parameters.

## 6.6 BULK TEMPERATURES-TEMPERATURE PROFILES-SCALING RESULTS

### 6.6.1 Introduction

Temperature data are presented in bulk-liquid temperature-time curves, and temperature profiles at normalized time  $\tau = 1.0$  for each test in both the dimensional and nondimensional forms. The temperature is nondimensionalized by dividing it by the characteristic temperature  $(q_H'' D/k_\ell)$  which is constant for any set of scaled tests. Temperature profile curves at several stratification test times as well as and the liquid, ullage, and tank structure temperature data for each test are presented in Volume II.

The bulk liquid temperature histories for the stratification scaling tests scaled to within 3 percent. However, a greater deviation was found when

Table 6-3  
PRESSURE DEVIATION (PERCENT  
(SCALING TESTS))

8G Tests—6-In.-Dia Tank/ 1G Tests—12-In.-Dia Tank			Gr <sub>H</sub> *	Deviation (Percent)
	50% Fill	Liquid Heating	10 <sup>14</sup>	4.4
		Liquid-Ullage Heating	10 <sup>14</sup>	16.2
	87.5% Fill	Liquid Heating	10 <sup>14</sup>	5.1
			7 x 10 <sup>14</sup>	1.8
			10 <sup>15</sup>	2.0
		Liquid-Ullage Heating	10 <sup>14</sup>	16.0
			7 x 10 <sup>14</sup>	27.8
			10 <sup>15</sup>	23.0
27G Tests—6-In.Dia Tank/ 1G Tests—18-In.-Dia Tank				
	50% Fill	Liquid Heating	10 <sup>15</sup>	4.9
	87.5% Fill	Liquid Heating	10 <sup>16</sup>	5.2

making a pointwise comparison of the temperature profiles for the scaled tests.

#### 6.6.2 Temperature Scaling Results

##### 6.6.2.1 Bulk Temperatures

Nondimensional and dimensional bulk liquid (Freon 113) temperature history curves are shown for the stratification scaling tests in Figures 6-62 through 6-71. The normalized bulk liquid temperature history curves indicate that the scaled tests agree where the curves match well for both the liquid and liquid-ullage heating conditions. The bulk temperature reflects the integrated temperature effect of the heat absorbed by the liquid and is a measure of the tank-system scaling concept studied in this program. Hence, qualitatively, the curves indicate that the total energy transferred to the liquid has been scaled reasonably well.



SCALING TEST DATA  
BULK LIQUID TEMPERATURE HISTORIES  
(FREON 113 (PCA))

FIGURES 6-62 THROUGH 6-71

NOMENCLATURE

$Gr_H^*$ . . . . .	Modified Grashof number based on input heater heat-flux source, $(g\beta_\ell q_H'' L^4/k_\ell \nu_\ell^2)$
$g$ . . . . .	Gravitational constant
$\beta_\ell$ . . . . .	Liquid coefficient of thermal expansion, $(\frac{1}{\rho_\ell} \frac{\partial \rho_\ell}{\partial T})$
$\rho_\ell$ . . . . .	Liquid density
$T$ . . . . .	Measured temperature ( $^{\circ}F$ )
$q_H''$ . . . . .	Measured input heat heat flux source, Btu/hr-ft <sup>2</sup>
$L$ . . . . .	Liquid depth
$k_\ell$ . . . . .	Liquid thermal conductivity
$\nu_\ell$ . . . . .	Liquid kinematic viscosity, $(\mu_\ell/\rho_\ell)$
$\mu_\ell$ . . . . .	Liquid dynamic viscosity
$D$ . . . . .	Tank diameter
CHTMP . . . . .	Characteristic temperature, $(q_H'' D/k_\ell)$
$\bar{T}$ . . . . .	Normalized temperature, $(T/CHTMP)$
$\tau$ . . . . .	Normalized time, $(t/\theta)$
$t$ . . . . .	Elapsed test time
$\theta$ . . . . .	Stratification test time
6 in.-8G#12S . . . . .	Test title (e. g., 6-inch diameter tank - 8 g's test number 12; "S" indicates no heating during destratification testing)

FIGURE 6-62  
SCALING TESTS DATA - BULK LIQUID TEMP HISTORIES,  
6 IN. 8G2 AND 12S - 12 IN. 1G30 AND 25

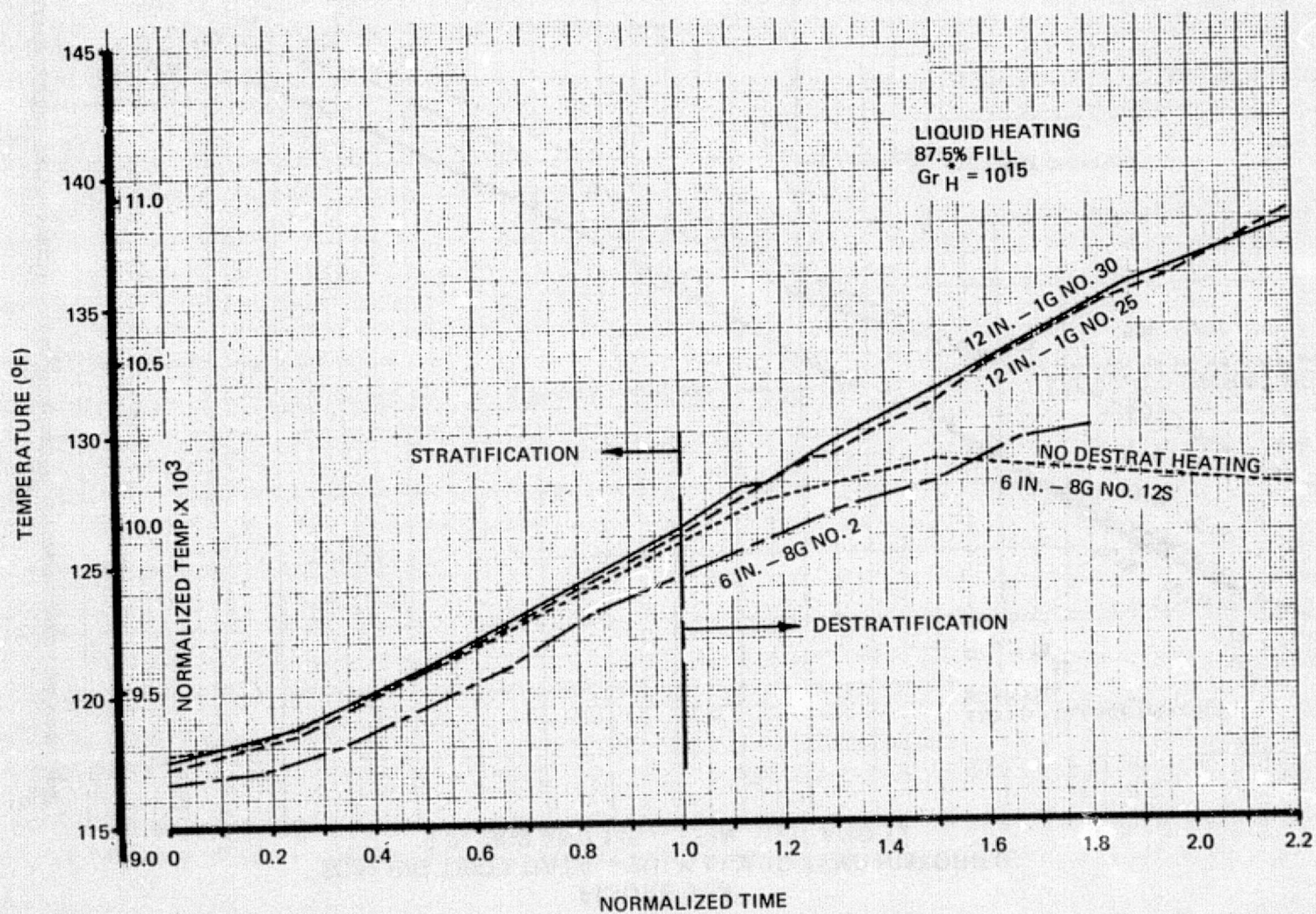


FIGURE 6-63  
SCALING TESTS DATA - BULK LIQUID TEMP HISTORIES,  
6 IN. 8G3 AND 11S - 12 IN. 1G31 AND 17

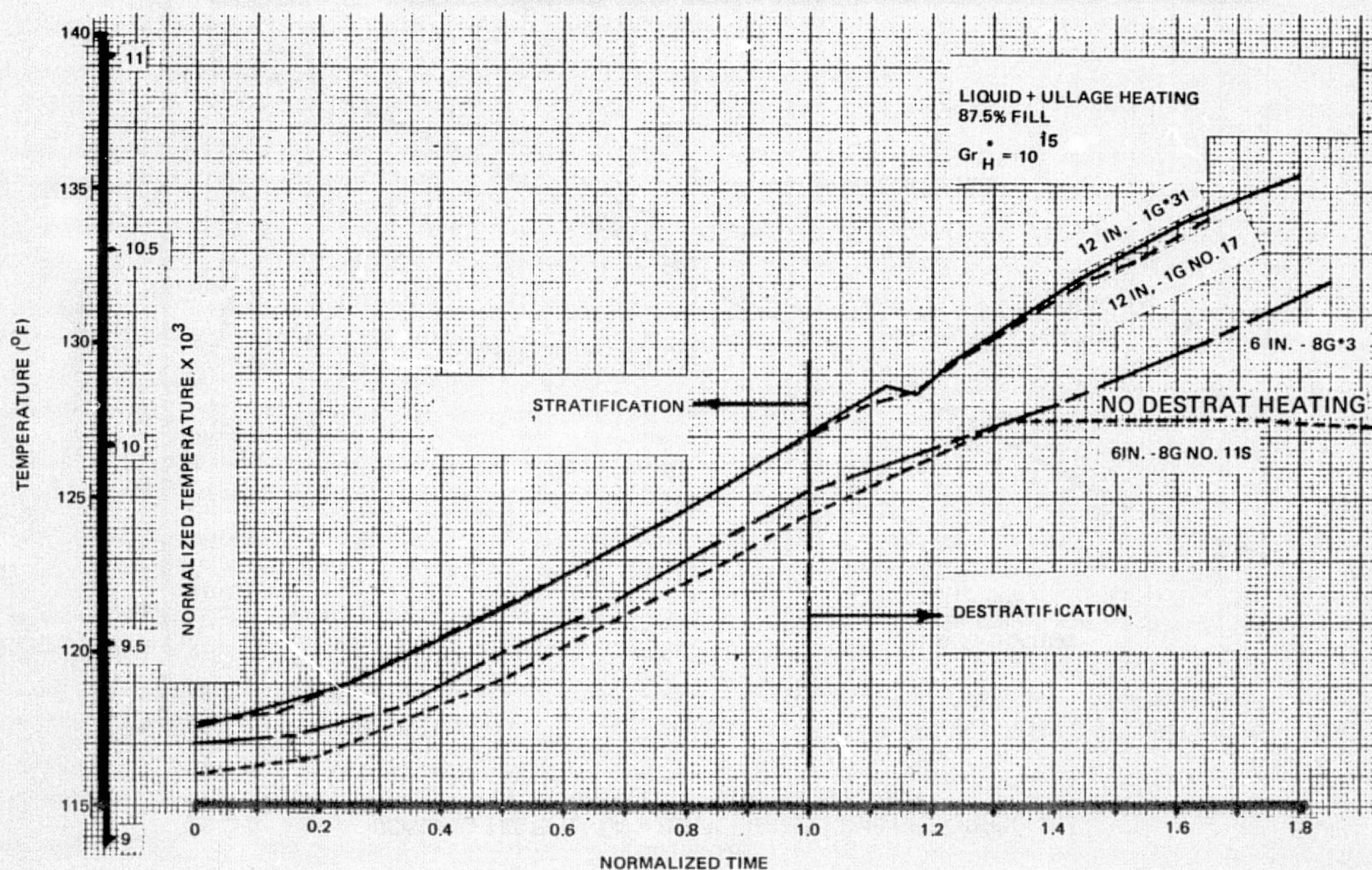




FIGURE 6-64  
SCALING TESTS DATA - BULK LIQUID TEMP HISTORIES,  
6 IN. 8G9S AND 15S - 12 IN. 1G33 AND 32

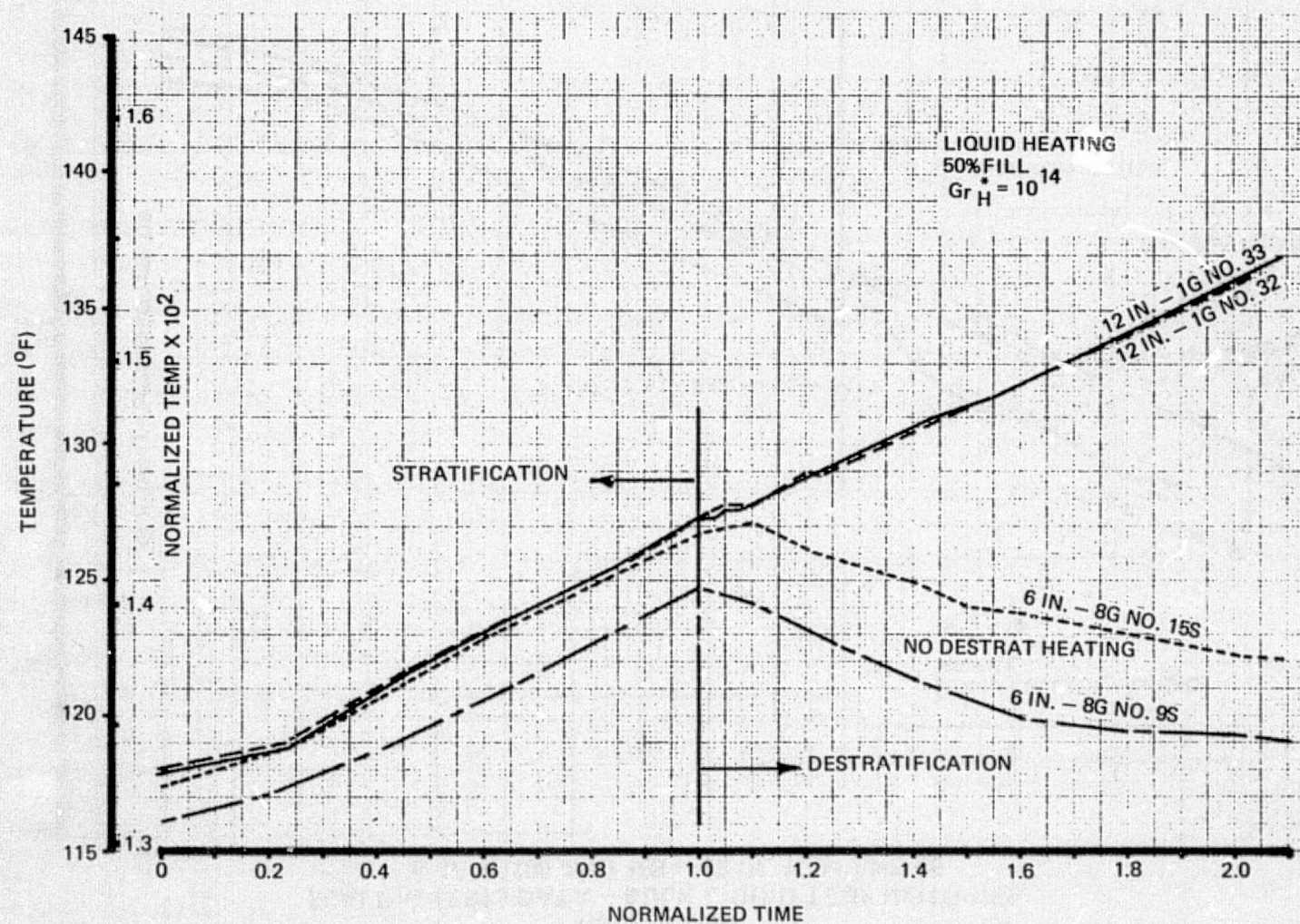




FIGURE 6-65  
SCALING TESTS DATA - BULK LIQUID TEMP HISTORIES,  
6 IN. 8G10S AND 16S - 12 IN. 1G34 AND 35

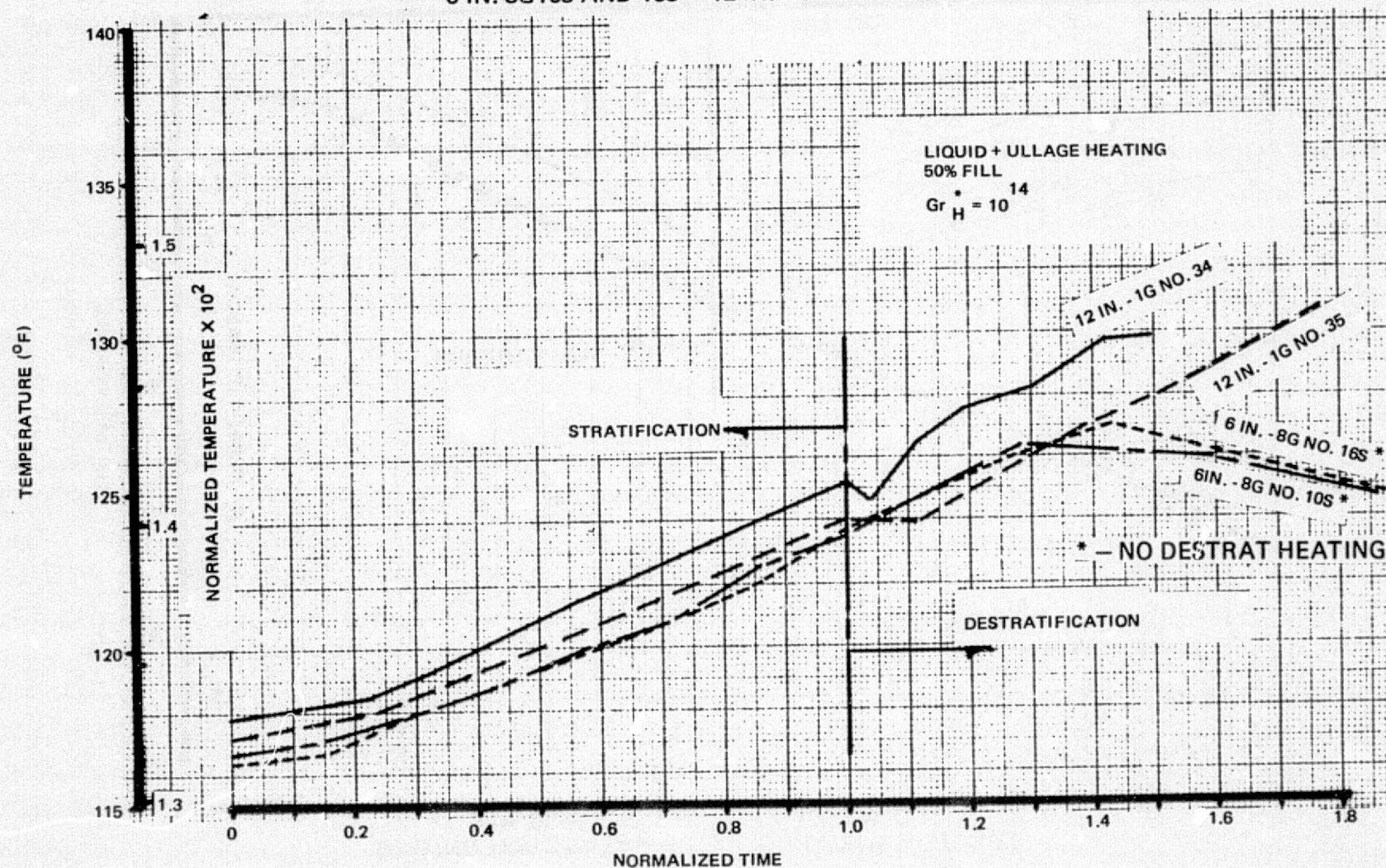


FIGURE 6-66  
SCALING TESTS DATA - BULK LIQUID TEMP HISTORIES,  
6 IN. 8G1, 5 AND 8S - 12 IN. 1G22 AND 20

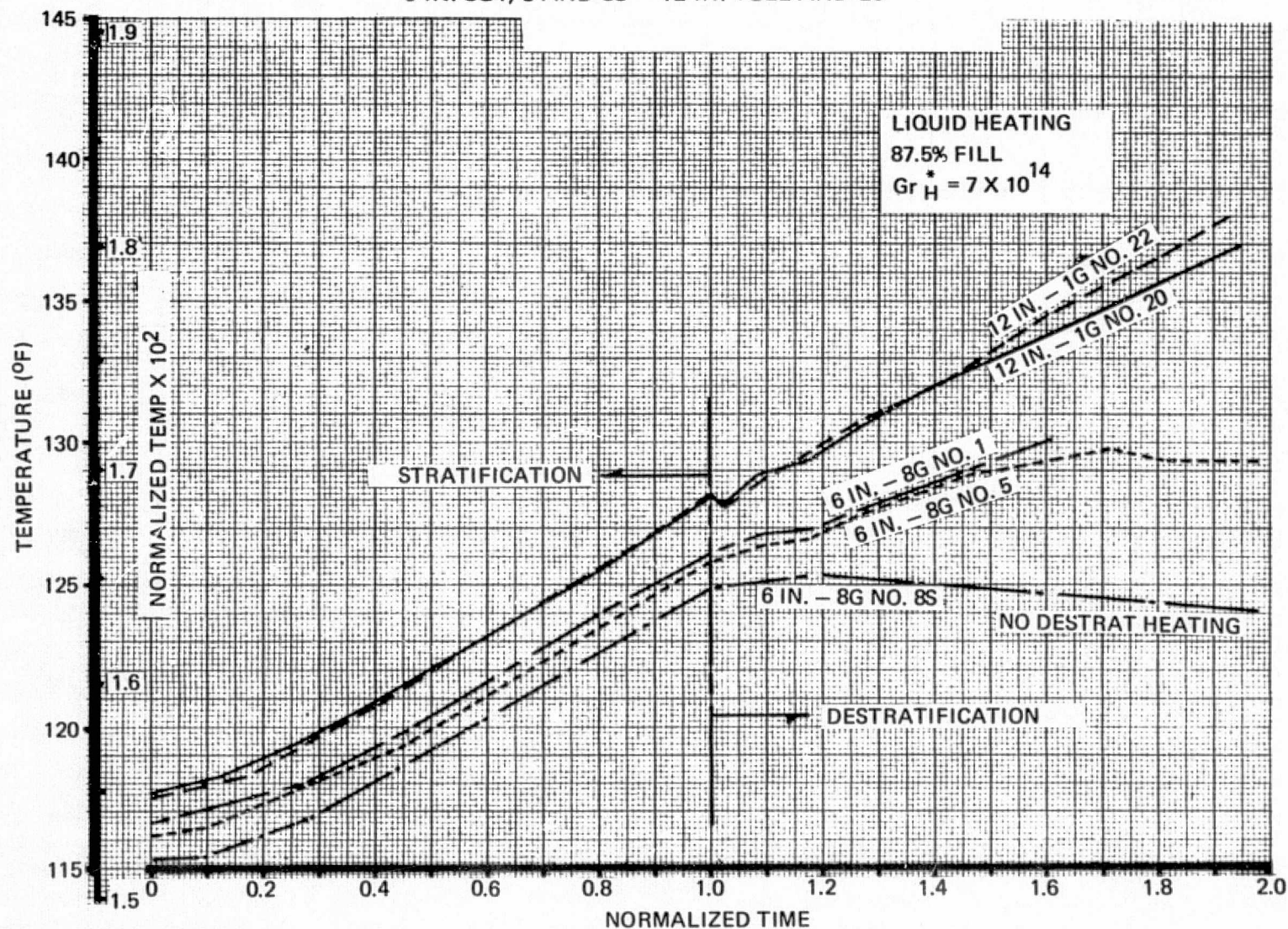




FIGURE 6-67  
SCALING TESTS DATA - BULK LIQUID TEMP HISTORIES,  
6 IN. 8G4 AND 6 - 12 IN. 1G23 AND 28

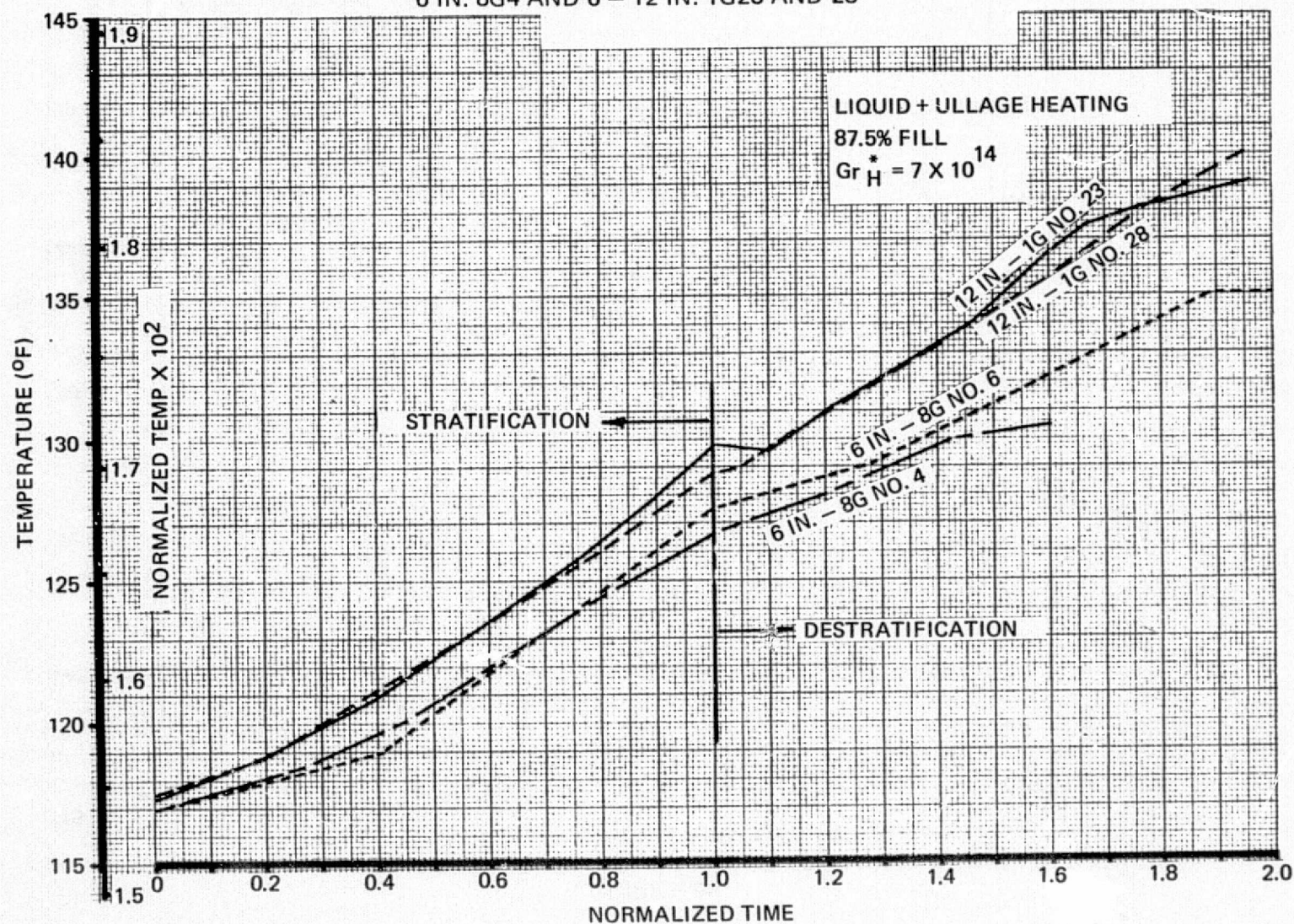


FIGURE 6-68  
SCALING TESTS DATA - BULK LIQUID TEMP HISTORIES,  
6 IN. 27G1S - 18 IN. 1GBS AND D

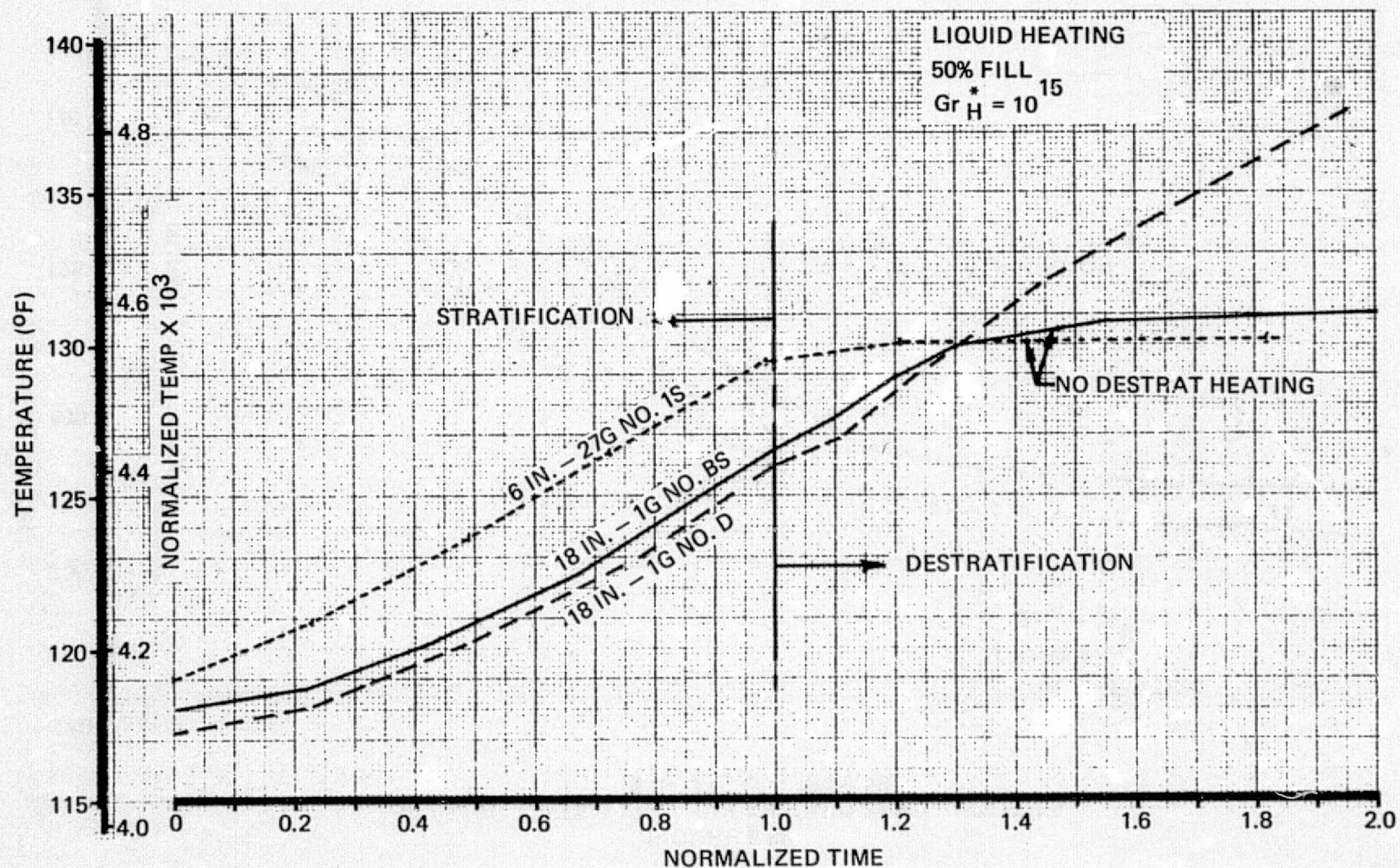




FIGURE 6-69  
SCALING TESTS DATA - BULK LIQUID TEMP HISTORIES,  
6 IN. 27G3S - 18 IN. IS

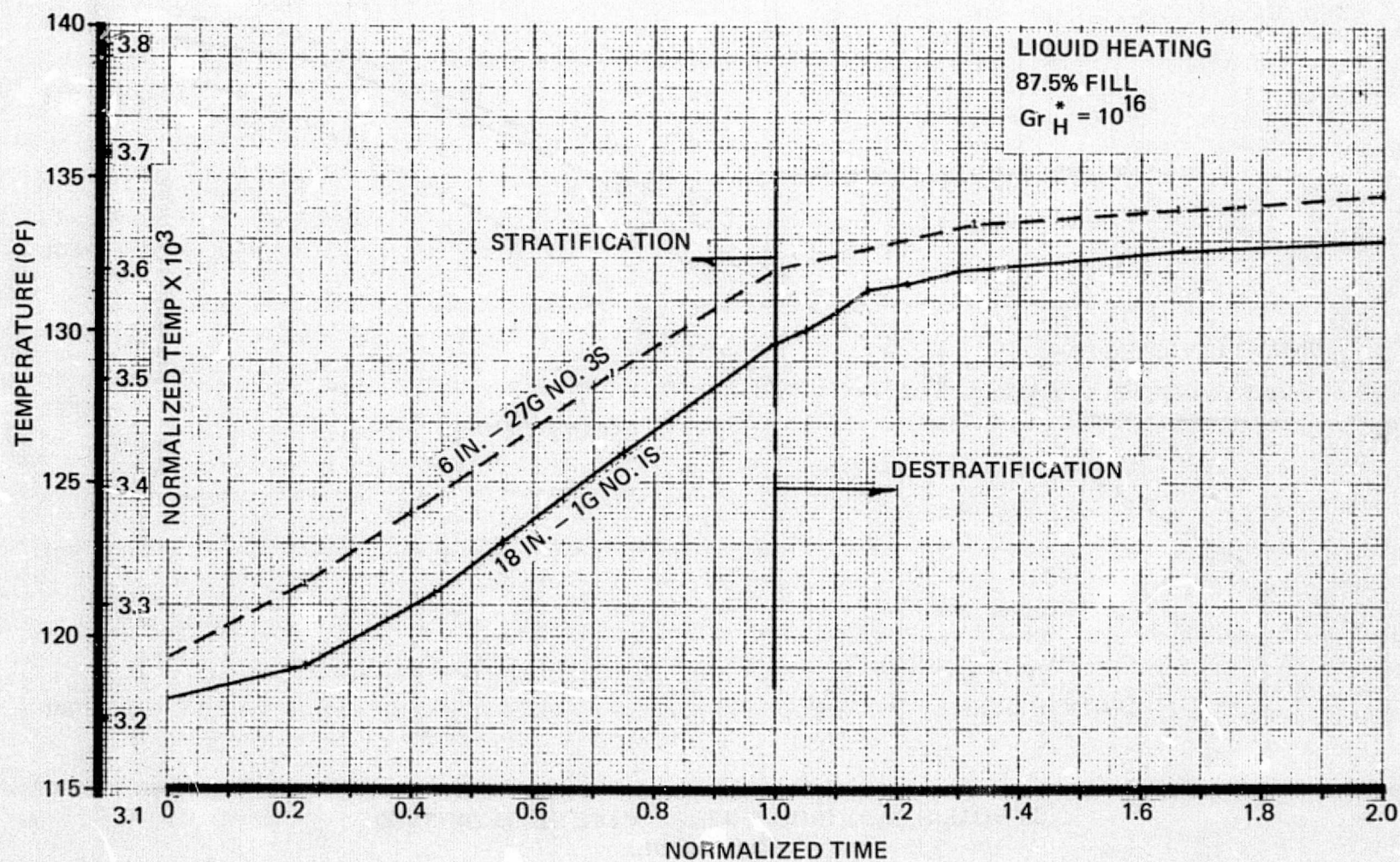


FIGURE 6-70  
SCALING TESTS DATA — BULK LIQUID TEMP HISTORIES,  
6 IN. 8G14 — 12 IN. 1G26 AND 15

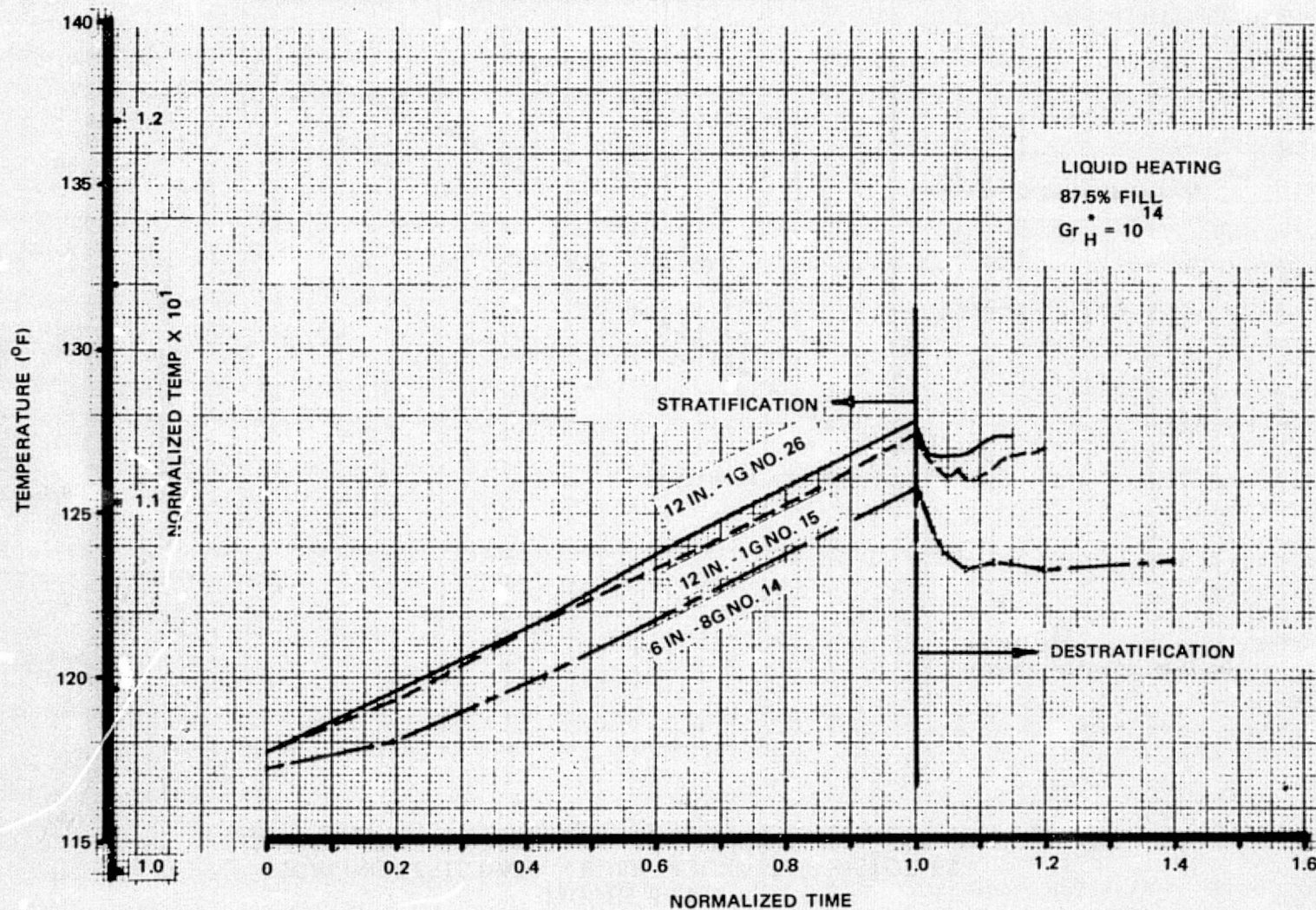
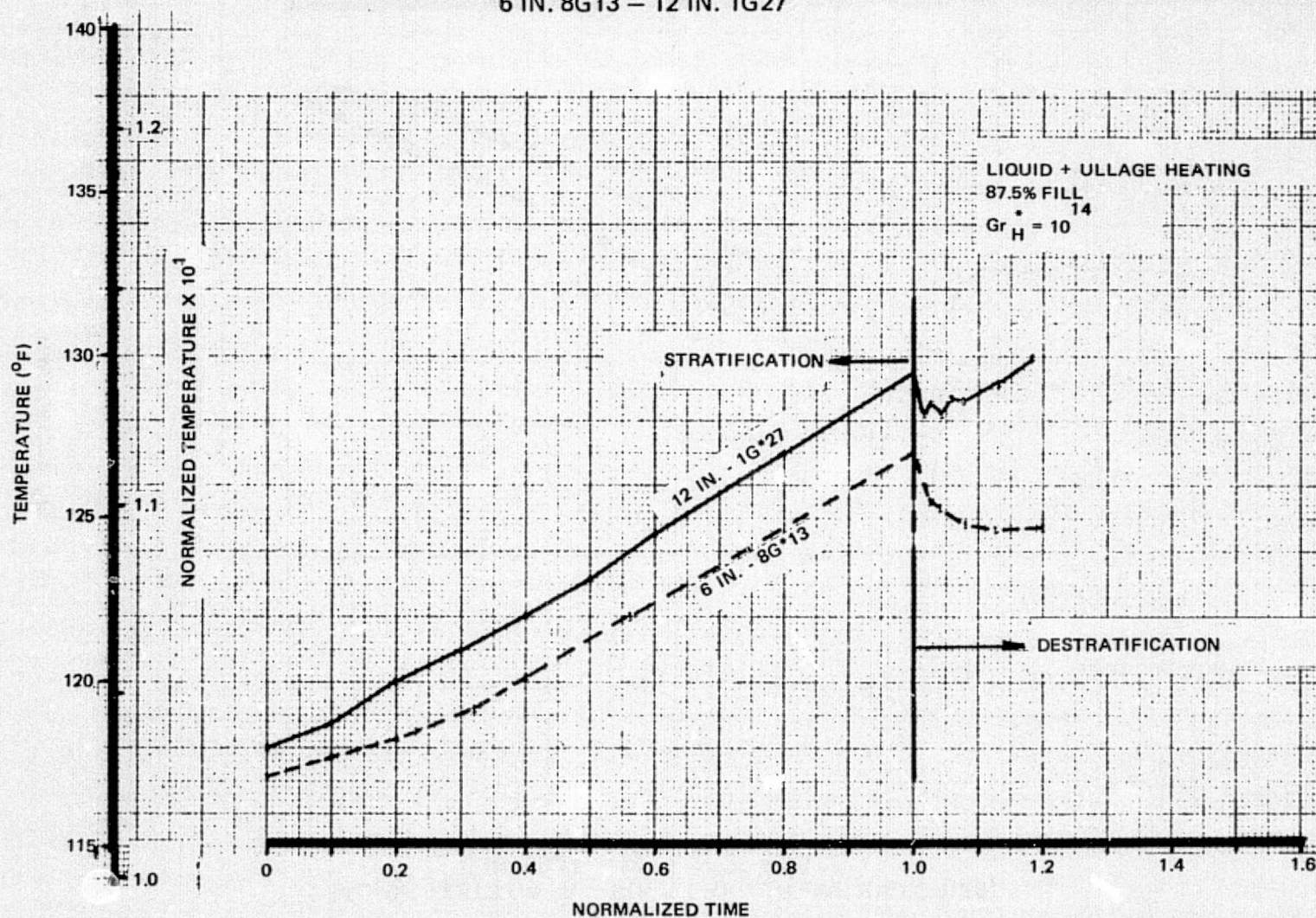




FIGURE 6-71  
SCALING TESTS DATA - BULK LIQUID TEMP HISTORIES  
6 IN. 8G13 - 12 IN. 1G27



A quantitative look at the degree of scaling or matching of the bulk temperature data is shown in Table 6-4. This table shows that the bulk liquid temperature curves scale to within a 2.5 percent deviation. The basis for these estimates is discussed in Subsection 6.2.2 (Equation 6-1). The differences expressed in these values and in Figures 6-62 through 6-71 may be directly related to the measured Modified Grashof number variations ( $Gr_l^*$ ) discussed in Subsection 6.3.1.

#### 6.6.2.2 Temperature Profiles

Although the bulk-liquid temperature data show that the scaling criterion  $\bar{T}_{bA}(\tau) = \bar{T}_{bB}(\tau)$  is met to within a 2.5 percent deviation, the additional criterion of  $\bar{T}_A(\bar{x}, \bar{y}, \bar{z}, \tau) = \bar{T}_B(\bar{x}, \bar{y}, \bar{z}, \tau)$  must also be satisfied. The delta temperature and normalized delta temperature profiles for the scaled tests at the end of the stratification period ( $\tau = 1.0$ ) are compared below.

Table 6-4  
MAXIMUM BULK TEMPERATURE DEVIATIONS (PERCENT)  
(SCALING TESTS)

8G Tests—6-In.-Dia Tank/ 1G Tests—12-In.Dia Tank			$G_{IH}^*$	Deviation (Percent)
	50% Fill'	Liquid Heating	$10^{14}$	0.8
		Liquid-Ullage Heating	$10^{14}$	0.5
	87.5% Fill	Liquid Heating	$10^{14}$	1.4
			$7 \times 10^{14}$	1.1
			$10^{15}$	0.9
		Liquid-Ullage Heating	$10^{14}$	1.4
			$7 \times 10^{14}$	2.5
			$10^{15}$	0.9
27G Tests—6-In.-Dia Tank/ 1G Tests—18-In.-Dia Tank				
50% Fill	Liquid Heating	$10^{15}$	1.7	
87.5% Fill	Liquid Heating	$10^{16}$	0.9	



These normalized delta temperature profiles at  $\tau = 1.0$  for scaled tests are shown in Figures 6-72 through 6-81. The data show that there are differences in the normalized profiles for the scaled tests. Because of the high degree of repeatability of the liquid-bulk temperature as well as the point-by-point profile agreement, it is likely that these differences are largely due to real thermodynamic and fluid dynamic differences in the separate tanks. It should be noted, however, that the difference in temperature profiles of a scaled pair of tank tests was found to be greater than that between profiles for the same tank even when  $Gr_H^*$  differed by about an order of magnitude. This is illustrated in Figures 6-72 through 6-81 which show that the axial temperature gradient for the 6-inch tank at the 8-g and 27-g levels exceeds the 12-inch and 18-inch tank gradients at 1 g for each scaled set of tests. This was found to be true for both 50 and 87.5 percent fill levels. Furthermore, Figure 6-82 shows that for the same 6-inch tank and for values of  $Gr_H^*$  from  $10^{14}$  to  $7 \times 10^{14}$ , that the temperature gradient difference was significantly less than that between scaled tests. This would seem to imply that there is an inherent difference in each of the tanks which may or may not be related to the scaling effect. Unfortunately insufficient data are available to pinpoint the cause of the tank-to-tank variations although the fact that the heater blankets were all of the same thickness may be a contributing factor.

A quantitative assessment of the variations in the liquid-scaling temperature profiles was made by determining the percent deviation of the liquid-temperature profile slopes for the scaled tests. This was done by first determining the area under the profile curves. Then an average stratification temperature profile slope was determined for each curve. The percent deviation for each set of scaled data was then determined by dividing the difference in the liquid profile slopes by the mean slope for the scaled tests as shown:

$$\text{PROFILE DEVIATION} = \frac{\left| \left( \frac{\partial T}{\partial y} \right)_{1,f} - \left( \frac{\partial T}{\partial y} \right)_{2,f} \right|}{\frac{1}{2} \left| \left( \frac{\partial T}{\partial y} \right)_{1,f} + \left( \frac{\partial T}{\partial y} \right)_{2,f} \right|} \quad (6-8)$$

Hence, Table 6-5 shows the profile percent deviations for the scaled experiments. These values are a relative measure of the deviation of the point-by-point liquid-temperature scaling requirement.

SCALING TEST DATA  
STRATIFICATION TEMPERATURE PROFILES ( $\tau = 1.0$ )

FIGURES 6-72 THROUGH 6-81

NOMENCLATURE

$Gr_H^*$ . . . . .	Modified Grashof number based on input heater heat flux source, $(g\beta_\ell q_H'' L^4/k_\ell \nu_\ell^2)$
$g$ . . . . .	Gravitational constant
$\beta_\ell$ . . . . .	Liquid coefficient of thermal expansion, $(\frac{1}{\rho_\ell} \frac{\partial \rho_\ell}{\partial T})$
$\rho_\ell$ . . . . .	Liquid density
$T$ . . . . .	Measured temperature ( $^{\circ}F$ )
$q_H''$ . . . . .	Measured input heater heat flux source, Btu/hr-ft <sup>2</sup>
$L$ . . . . .	Liquid depth
$k_\ell$ . . . . .	Liquid thermal conductivity
$\nu_\ell$ . . . . .	Liquid kinematic viscosity, $(\mu_\ell/\rho_\ell)$
$\mu_\ell$ . . . . .	Liquid dynamic viscosity
$D$ . . . . .	Tank diameter
CHTMP . . . . .	Characteristic temperature, $(q_H'' D/k_\ell)$
$\Delta T$ . . . . .	Del Tmp, $T(\tau) - T(\tau = 0)$
$\Delta \bar{T}$ . . . . .	Normalized Del Tmp, $(\Delta T/CHTMP)$
$\tau$ . . . . .	Normalized time, $(t/\theta)$
$t$ . . . . .	Elapsed test time
$\theta$ . . . . .	Stratification test time
6 in.-8G#12S . . . . .	Test title (e.g., 6-inch diameter - 8 g's test number 12; "S" indicates no heating during destratification testing)

FIGURE 6-72  
 SCALING TESTS DATA – STRATIFICATION TEMP PROFILES ( $\tau = 1.0$ )  
 6 IN. 8G2 AND 12S – 12 IN. 1G30 AND 25

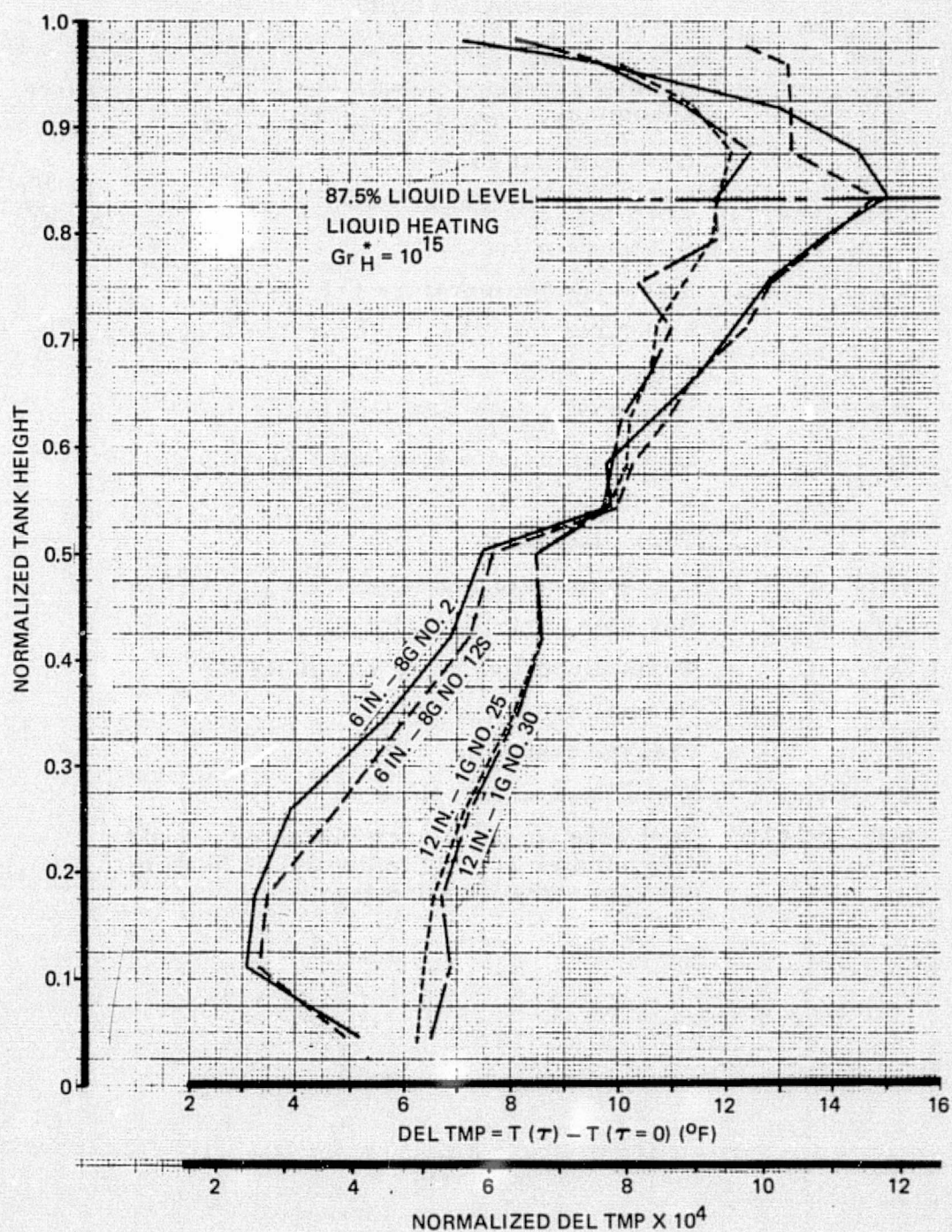


FIGURE 6-73  
SCALING TESTS DATA – STRATIFICATION TEMP PROFILES ( $\tau = 1.0$ )  
6 IN. 8G3 AND 11S – 12 IN. 1G31 AND 17

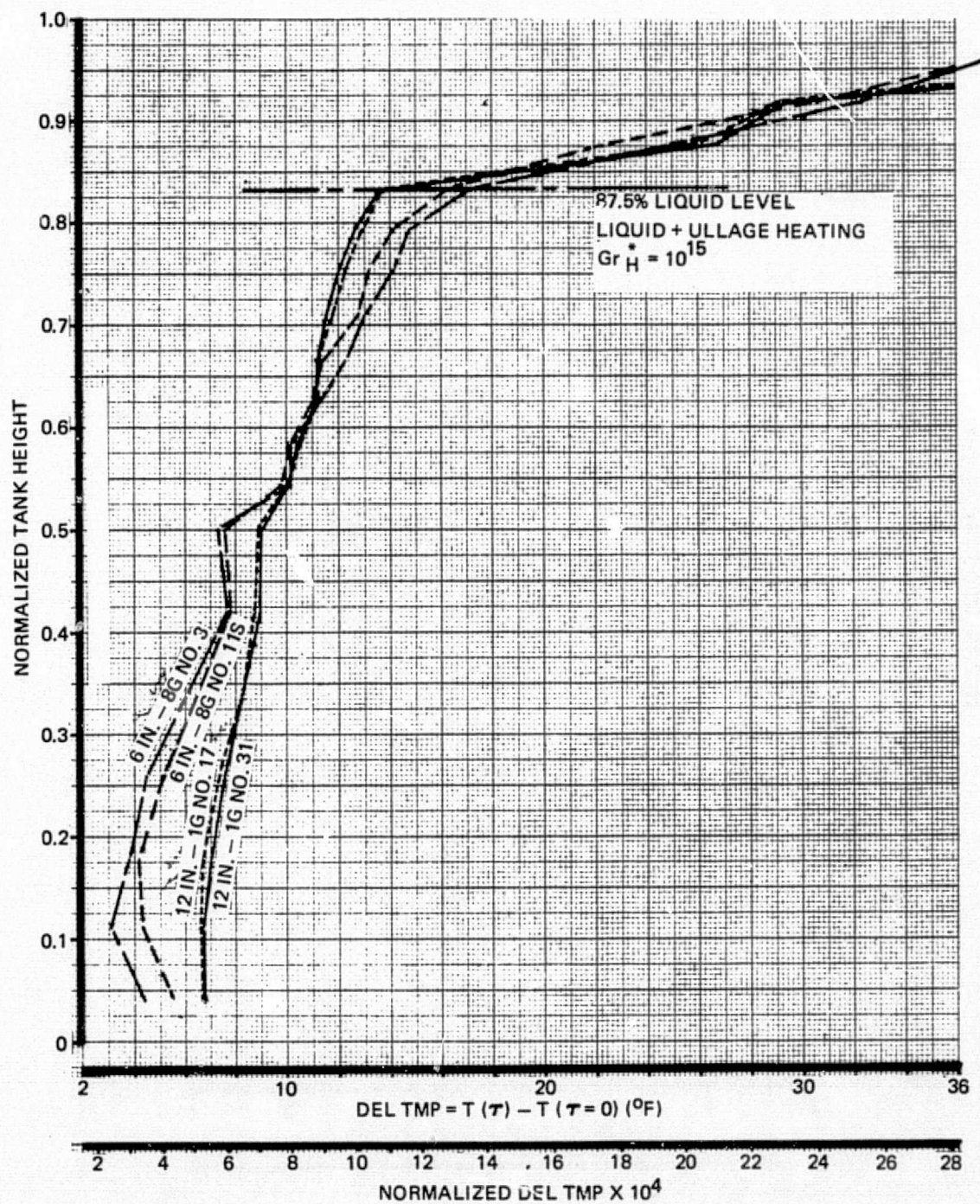




FIGURE 6-74  
 SCALING TESTS DATA — STRATIFICATION TEMP PROFILES ( $\tau = 1.0$ )  
 6 IN. 8G9S AND 15S — 12 IN. 1G33 AND 32

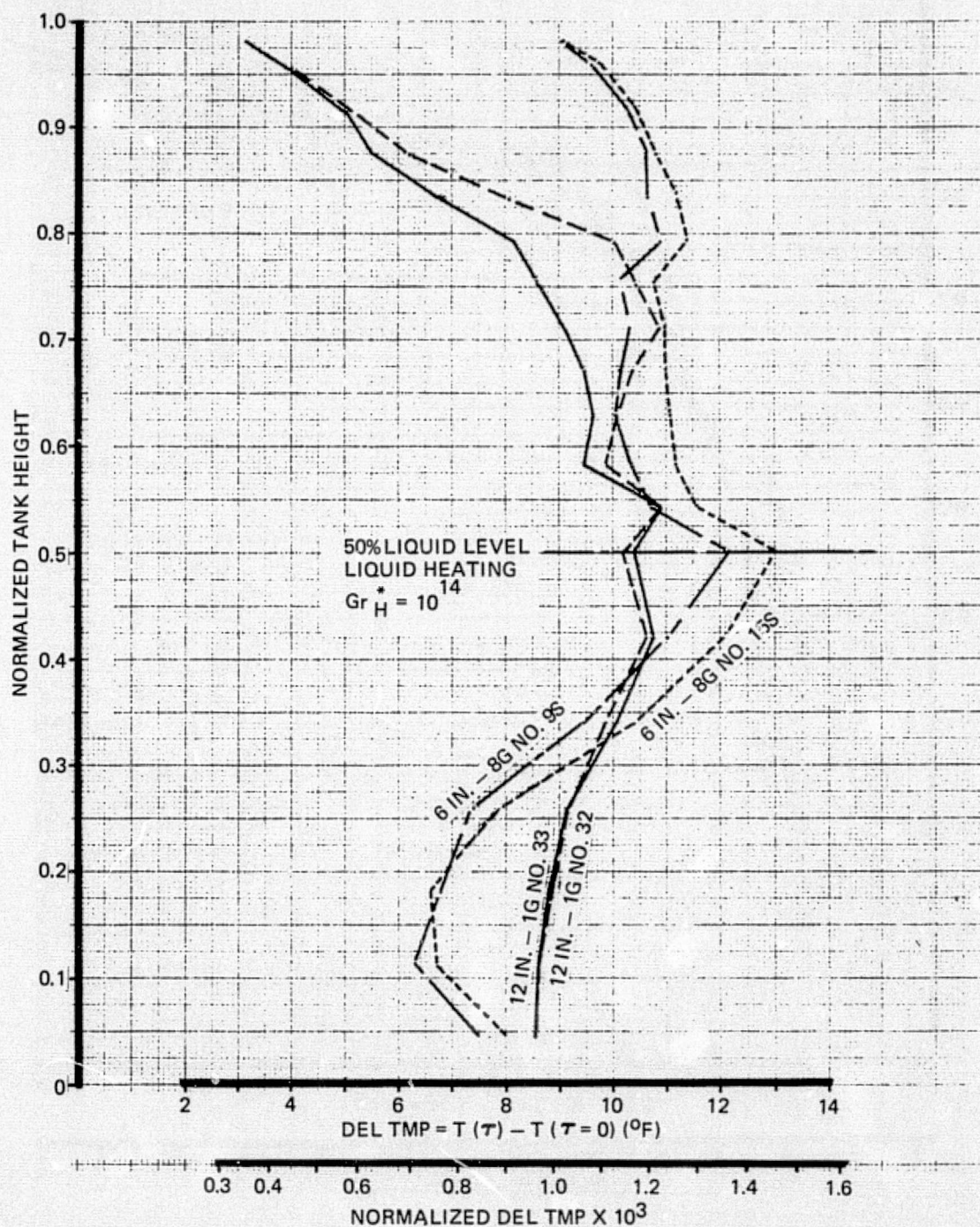


FIGURE 6-75  
 SCALING TESTS DATA - STRATIFICATION TEMP PROFILES ( $\tau = 1.0$ )  
 6 IN. 8G10S AND 16S - 12 IN. 1G34 AND 35

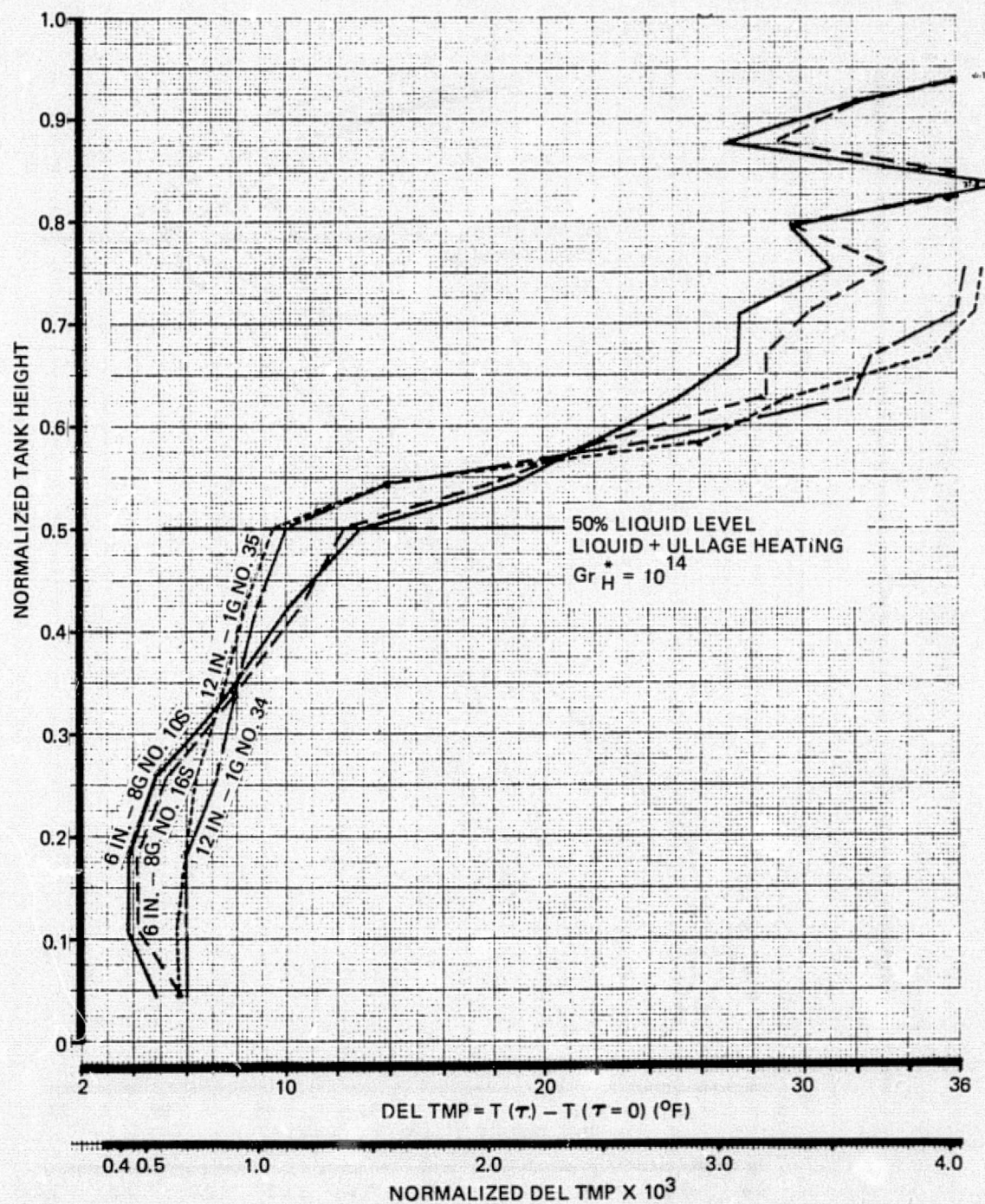




FIGURE 6-76  
 SCALING TESTS DATA – STRATIFICATION TEMP PROFILES ( $\tau = 1.0$ )  
 6 IN. 8G1, 5, AND 8S – 12 IN. 1G20 AND 22

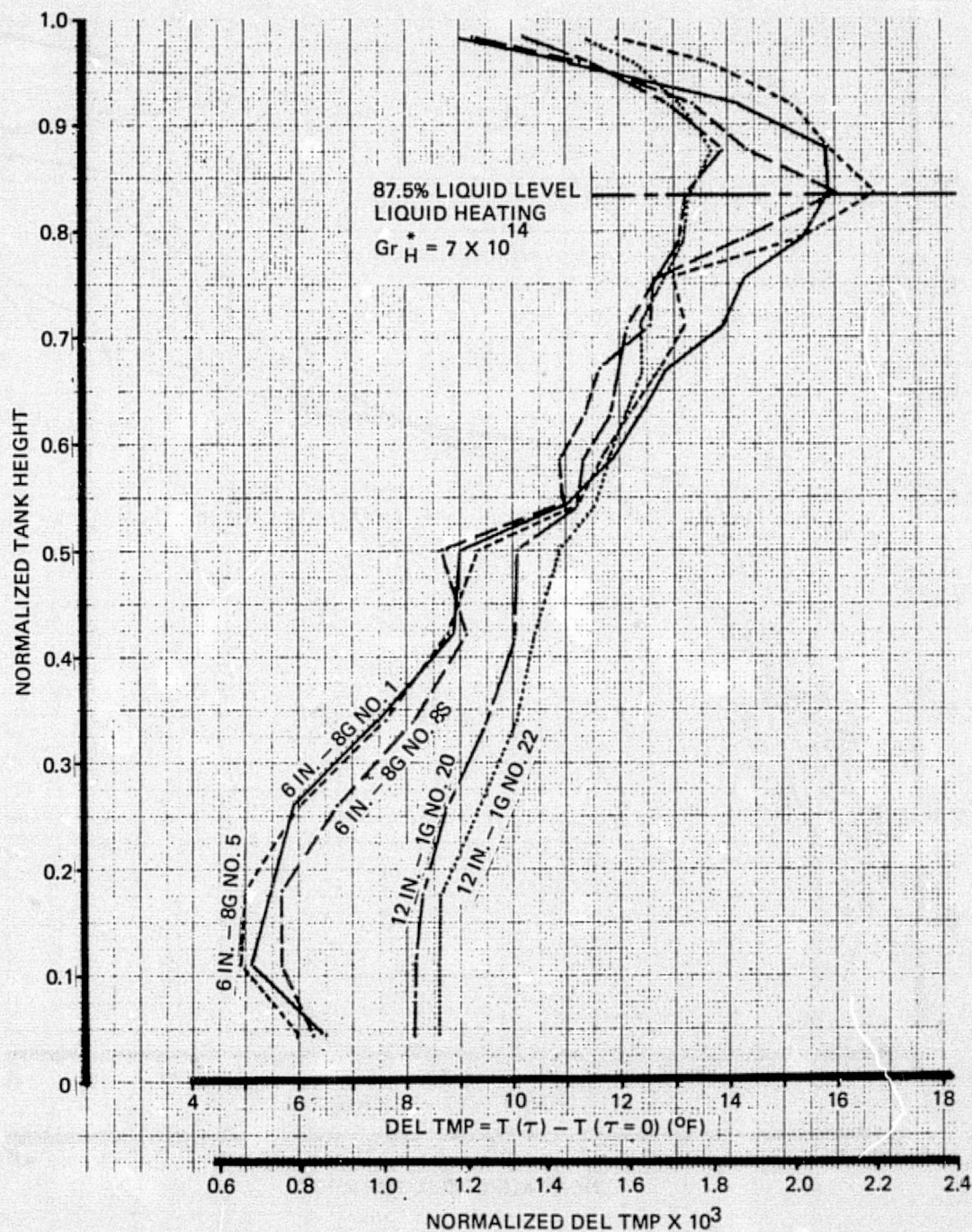


FIGURE 6-77  
 SCALING TESTS DATA – STRATIFICATION TEMP PROFILES ( $\tau = 1.0$ )  
 6 IN. 8G4 AND 6 – 12 IN. 1G23 AND 28

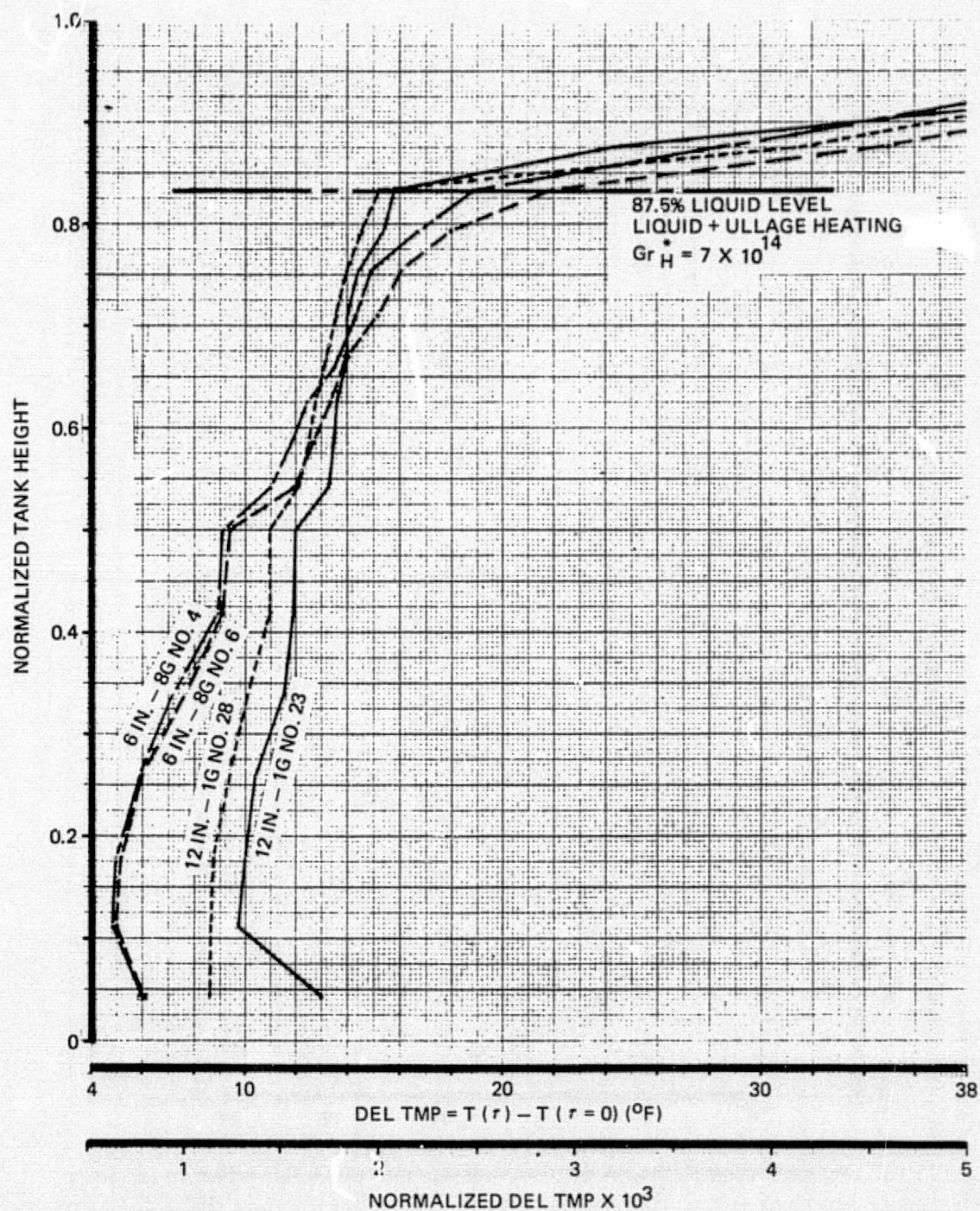




FIGURE 6-78  
 SCALING TESTS DATA – STRATIFICATION TEMP PROFILES ( $\tau = 1.0$ )  
 6 IN 27G1S – 18 IN. 1GBS AND D

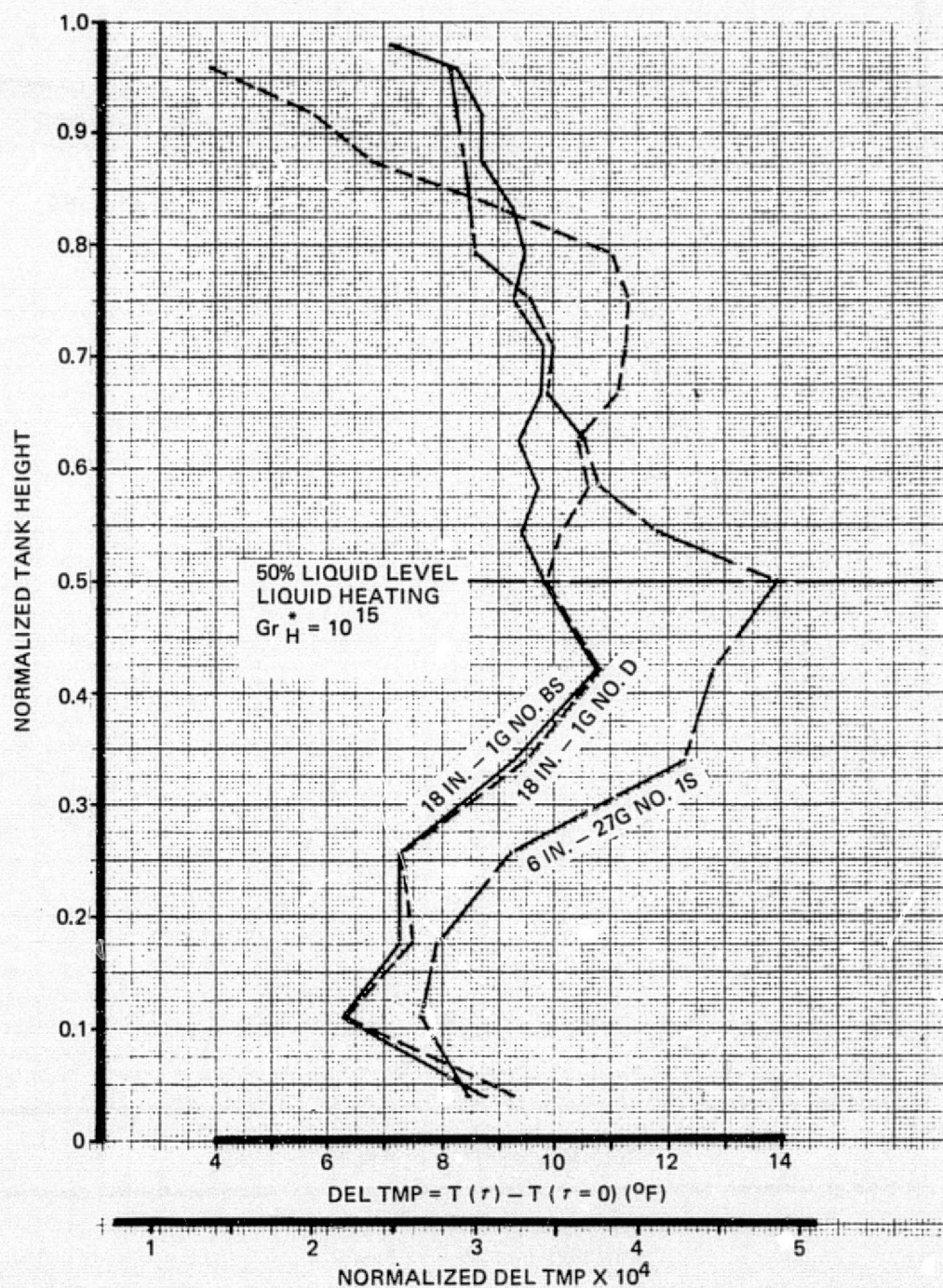


FIGURE 6-79  
 SCALING TESTS DATA – STRATIFICATION TEMP PROFILES ( $\tau = 1.0$ )  
 6 IN. 27G3S – 18 IN. 1G1S

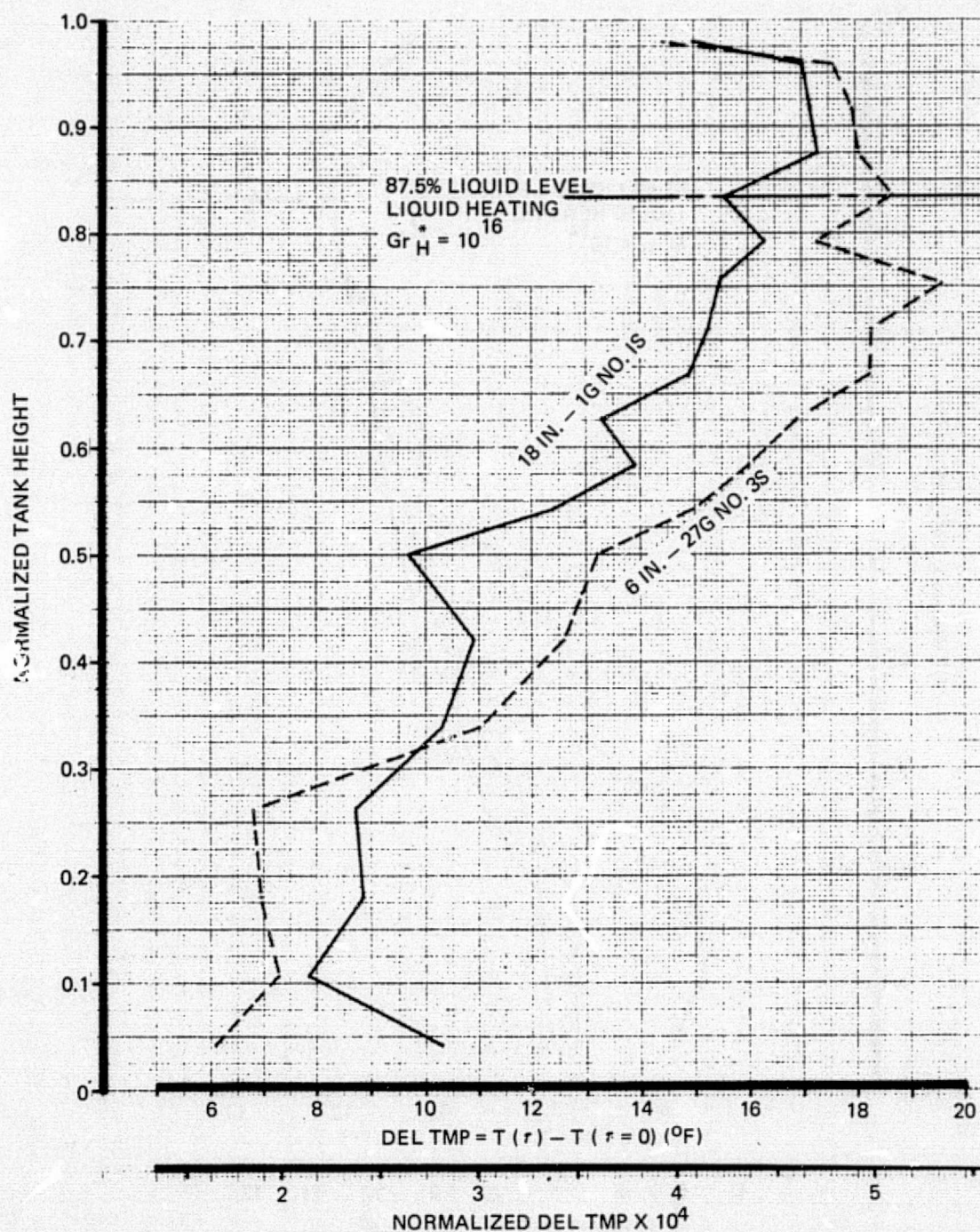




FIGURE 6-80  
 SCALING TESTS DATA – STRATIFICATION TEMP PROFILES ( $\tau = 1.0$ )  
 6 IN. 8G14 – 12 IN. 1G26 AND 15

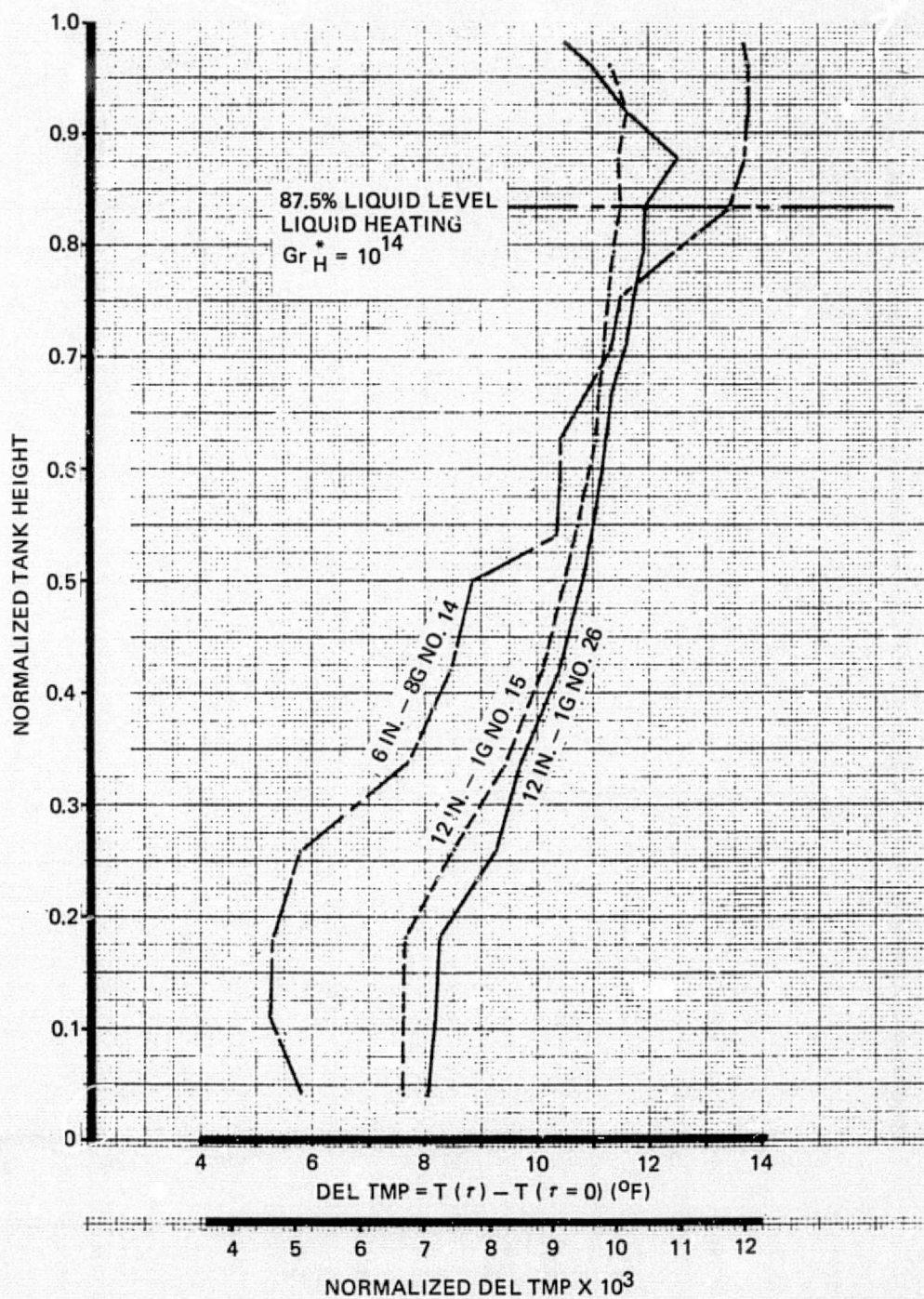
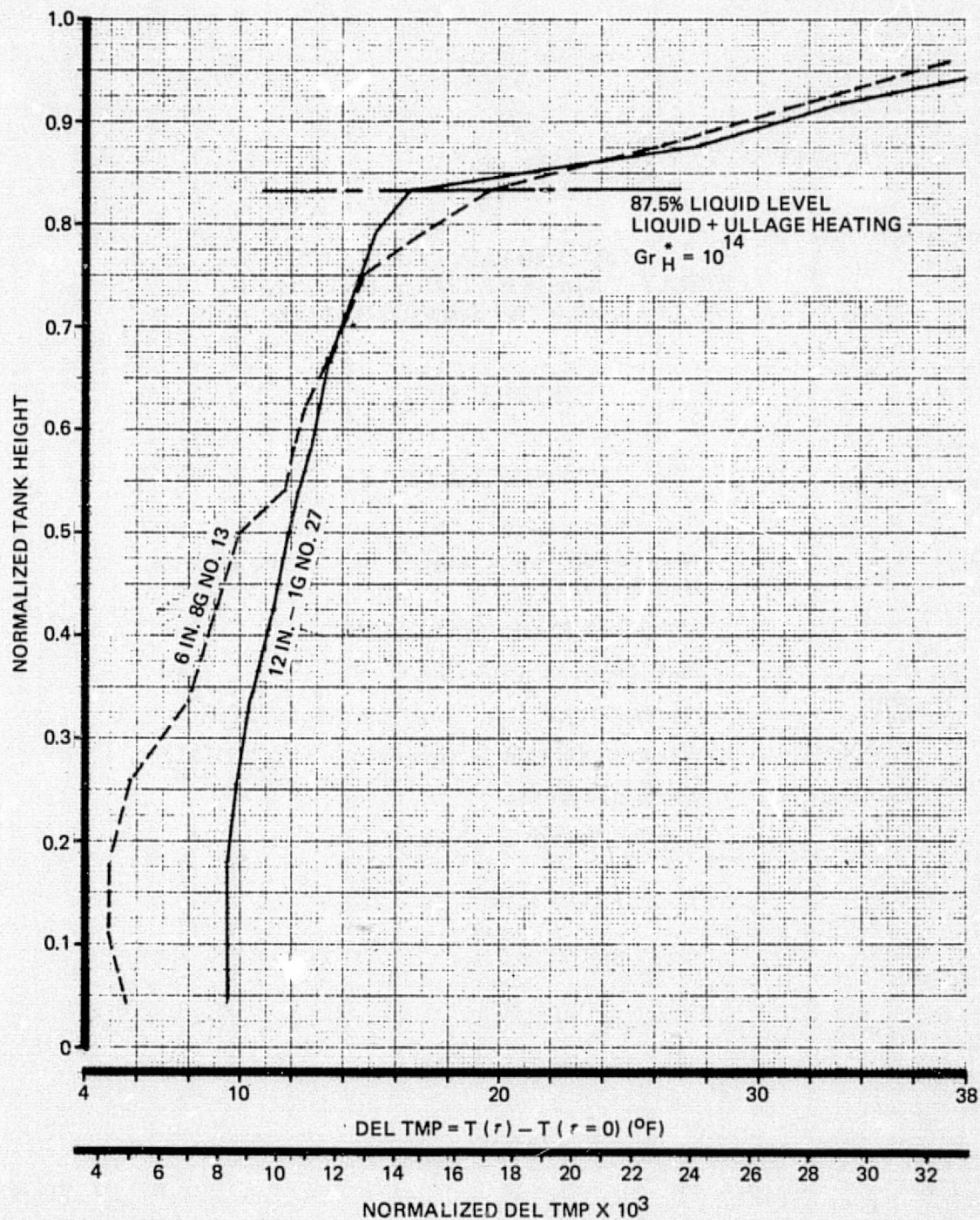


FIGURE 6-81  
 SCALING TESTS DATA — STRATIFICATION TEMP PROFILES ( $\tau = 1.0$ )  
 6 IN. 8G13 — 12 IN. 1G27





6-INCH DIAMETER TANK  
 STRAT TEMPERATURE PROFILES  
 ( $\tau = 1.0$ )—"G" DEPENDENCE

FIGURE 6-82

NOMENCLATURE

$q_H''$ . . . . .	Measured input heater heat-flux source, Btu/hr-ft <sup>2</sup>
T . . . . .	Measured temperature (°F)
$\Delta T$ . . . . .	Del Tmp, $T(\tau) - T(\tau = 0)$
$\overline{\Delta T}$ . . . . .	Normalized Del Tmp, $(\Delta T / \text{CHTMP})$
CHTMP . . . . .	Characteristic temperature, $(q_H'' D / k_\ell)$
D . . . . .	Tank diameter
$k_\ell$ . . . . .	Liquid thermal conductivity

FIGURE 6-82  
6 IN. TANK STRAT TEMP PROFILES ( $\tau = 1.0$ )  
"G" DEPENDENCE

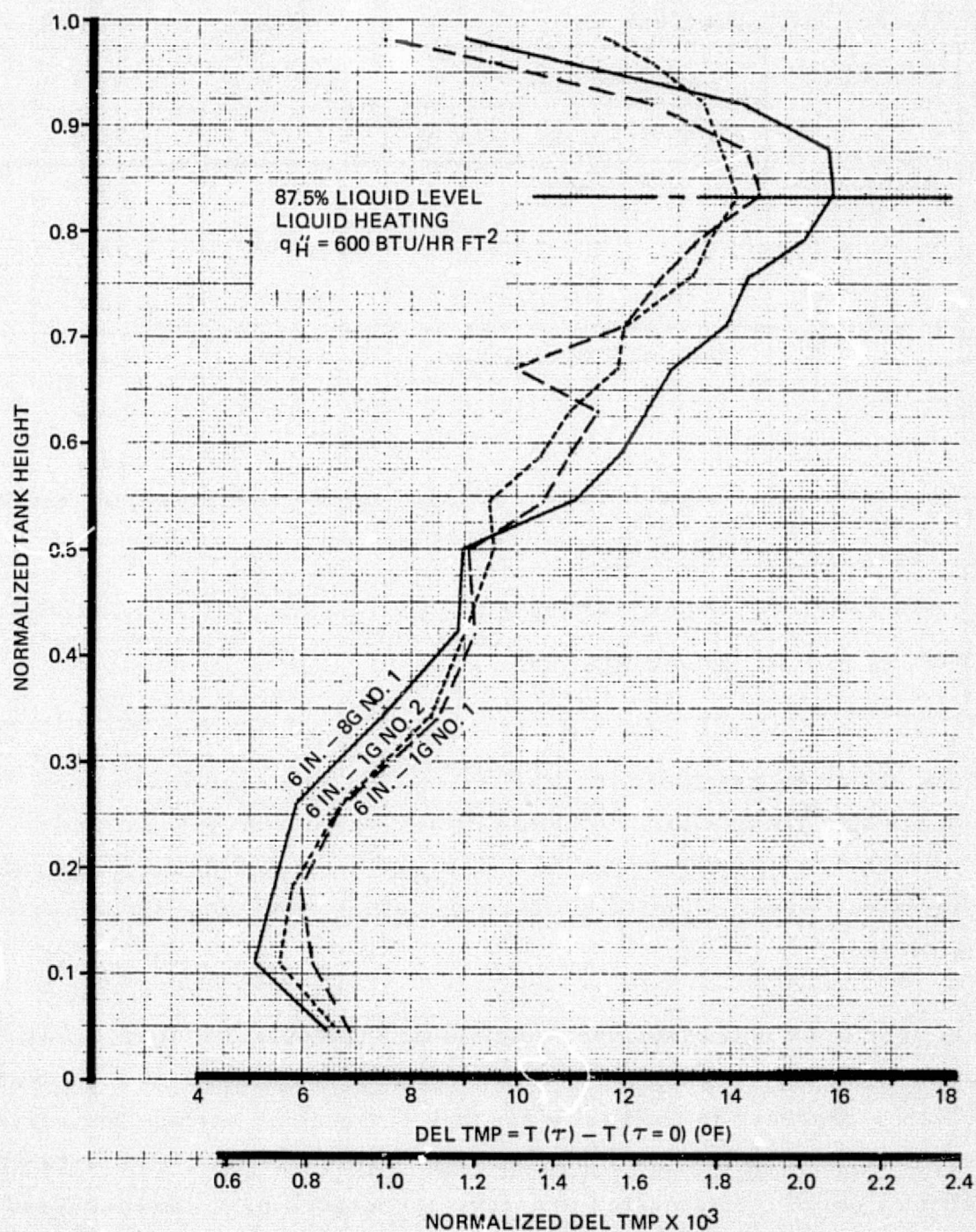




Table 6-5  
LIQUID STRATIFICATION TEMPERATURE PROFILE  
DEVIATION (PERCENT)  
(SCALING TESTS)

8G Tests—6-In.-Dia Tank/ 1G Tests—12-In.-Dia Tank			Gr <sub>H</sub> *	Deviation (Percent)
	50% Fill	Liquid Heating	10 <sup>14</sup>	39.1
		Liquid-Ullage Heating	10 <sup>14</sup>	32.4
	87.5% Fill	Liquid Heating	10 <sup>14</sup>	29.3
			7 x 10 <sup>14</sup>	35.3
			10 <sup>15</sup>	32.8
		Liquid-Ullage Heating	10 <sup>14</sup>	24.4
			7 x 10 <sup>14</sup>	29.8
			10 <sup>15</sup>	21.4
27G Tests—6-In.-Dia Tank/ 1G Tests—18-In.-Dia Tank				
	50% Fill	Liquid Heating	10 <sup>15</sup>	18.4
	87.5% Fill	Liquid Heating	10 <sup>16</sup>	10.1

Therefore, it can be concluded that the test system has been reasonably scaled to the bulk temperature deviation values which are approximately 3 percent (Table 6-4); whereas the scaling of the stratified liquid temperature profile (gradient) results in profile deviation values from 10 to 39 percent (Table 6-5).

However, it is to be noted that the liquid surface temperature differences, for the liquid heating only scaling tests, were within a range of about 3°F. Since the tank vapor pressure is indirectly coupled to the liquid surface temperature, it is interesting to note that the measured tank pressures for these tests were within about 1 psi of the saturated pressure corresponding to the measured Freon 113 liquid surface temperature. This was not true for those cases where the ullage was also heated.

## Section 7

### CONCLUSIONS

The experiments outlined in the matrix, Figure 5-1, have been conducted with three scaled cylindrical tanks, 6, 12, and 18 inches in diameter, with hemispherical domes having a tank length-to-diameter ratio of 3. These tests have been conducted with liquid (Freon 113) heating as well as with liquid and ullage heating, at both the 50 and 87.5-percent filling capacities, with heat flux values from 45 to 2,280 Btu/hr-ft<sup>2</sup>, Modified Grashof numbers ( $Gr_H^*$ ) from  $10^{14}$  through  $10^{16}$ , Fourier numbers from  $10^{-5}$  through  $10^{-4}$ , and Interface numbers from  $7.54 \times 10^{-3}$  through  $2.42 \times 10^{-1}$ . The experiments are compared in scaled sets by matching three dimensionless parameters (i.e.,  $Gr_H^*$ ,  $Fo$ , and Interface number) obtained in Subsection 2.5. The following conclusions can be drawn from these experiments:

- A. The bulk-liquid temperature for the stratification scaling tests was scaled to within 2.5 percent for all test configurations. The reproducibility data scatter of the bulk liquid temperature was less than 1 percent.
- B. The dimensionless tank pressure with liquid heating was scaled to within 5.1 percent. During the reproducibility tests, data scatter for these cases varied between 0.7 and 3.5 percent with one exception.
- C. The dimensionless tank pressure of two scaled tanks with liquid and ullage heating was scaled in the range of 16 to 28 percent. During the reproducibility tests, data scatter for this pressure and heating condition varied between 2 and 8.4 percent.
- D. The stratified liquid scaling profile deviation values showed that scaling was achieved in the range of 10 to 39 percent, although the liquid surface temperature deviation values were about the same as the pressure deviation values for the liquid heating only cases. The profile reproducibilities were nearly identical to one another; hence, the deviations were shown to be negligible.



In summary, the data reproducibility for the stratification experiments was good and, as a result, provided an excellent basis for comparing scaled tests. It has also been shown that the scaling criteria for the bulk temperature in all experiments and the tank pressure with liquid heating only were satisfied with respect to the pi-groups,  $Gr_H^*$ ,  $F_o$ , and  $L$ . Thus, it is concluded that these dimensionless parameters can be used to scale when the quantities which reflect the integrated heat transfer effects,  $\overline{T}_b$  and  $\overline{p}_v$ , are of interest. In addition, the temperature deviation values for the liquid surface were small. However, in general, deviations in the pointwise temperature  $\overline{T}(\overline{x}, \overline{y}, \overline{z}, \tau)$  for the scaled tests have been found but the data are insufficient to determine whether or not these deviations are due to the inadequacy of the pi groups or to a lack of scaling of the entire tank system with the constant heater thicknesses.

## Section 8

### RECOMMENDATIONS

The following recommendations are made within the context that the prediction of tank pressures for heated propellant tank systems is necessary. This report indicated that certain dimensionless parameters were necessary to define a heated container of liquid when considering pressure and bulk temperature. Thus, certain steps will have to be taken if the present state of the art is to be extended towards the above goal of making pressure and temperature predictions. These steps will include the extension of the experimental range so that correlations can be made, comparing these data obtained here with existing experimental correlations, and a further examination of the present data.

Hence the recommended steps to be continued from this program are primarily in three phases:

1. To evaluate and more fully understand the implications of the stratification (and destratification) data collected in this program.
2. Further testing to expand the range of parameters both for determining the important  $\pi$  groups and correlating the tank pressure and stratified liquid temperature profiles with the important scaling parameters.
3. Comparing data obtained here with existing experimental correlations.
4. Using latest experimental correlations modify an existing or develop a new model to predict tank pressure and propellant temperatures.

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Appendix A  
LIQUID AND ULLAGE PROPERTIES

This appendix contains the test liquid (Freon 113 PCA) and ullage properties, and the characteristic temperature and pressures for each experimental test investigated. Also shown are the values for the three scaling parameters that were maintained constant for the scaling test in this study. These parameters are the Modified Grashof number ( $Gr_H^*$ ), the Fourier number ( $Fo$ ), and the Interface number ( $I$ ). This information is shown in Table A-1.

Notes:

- $q_H''$  . . . . . Measured heater heat-flux source, Btu/hr-ft<sup>2</sup>
- $q_l''$  . . . . . Determined heat flux from heat absorbed by liquid,  
Btu/hr-ft<sup>2</sup>
- $\tau = 1$  . . . . . Normalized time at end of stratification test.
- CHTMP . . . . . Characteristic temperature, ( $q_H'' D/k$ )
- CHPRESS . . . . . Characteristic pressure, ( $q_H'' \theta/D$ )

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Table A-1  
FREON 113 PCA LIQUID - ULLAGE PRO

Test No.	6 in. 8G #9S	6 in. 8G #2	6 in. 8G #1	6 in. 8G #
Characteristic Temperature (CHTMP) (°F)	8.861 + 03	1.267 + 04	7.595 + 03	1.140 + 03
Characteristic Pressure (CHPRESS) (lb <sub>f</sub> /in. <sup>2</sup> )	4.211 + 02	3.609 + 02	3.96 + 02	4.058 + 02
LIQUID: density (lb/ft <sup>3</sup> )	94.431 - 93.656	94.382 - 93.681	94.387 - 93.529	94.335 - 93.5
mass (lb)	12.361 - 12.259	21.621 - 21.46	21.622 - 21.425	21.61 - 21.43
specific heat (Btu/lb °F)	0.225 - 0.227	0.225 - 0.227	0.225 - 0.227	0.225 - 0.227
thermal conductivity (Btu/hr ft °F)	0.04 - 0.039	0.04 - 0.039	0.04 - 0.039	0.04 - 0.039
viscosity (lb/ft hr)	1.202 - 1.137	1.198 - 1.139	1.198 - 1.127	1.194 - 1.113
kinematic viscosity (ft <sup>2</sup> /hr)	0.012732 - 0.012139	0.01269 - 0.01216	0.012696 - 0.012049	0.01265 - 0.0
Prandtl No.	6.834 - 6.6116	6.819 - 6.6185	6.82 - 6.578	6.805 - 6.587
Modified Grashof No. = $f(q_H'', \tau = 1.)$ , $Gr_H^*$	1.222 + 14	1.342 + 15	8.217 + 14	1.228 + 14
Modified Grashof No. = $f(q_L'', \tau = 1.)$ , $Gr_L^*$	6.412 + 13	7.8 + 14	5.32 + 14	6.999 + 13
Interface No., I	0.03106	0.0218	0.0363	0.242
ULLAGE: density (lb/ft <sup>3</sup> )	0.451 - 0.531	0.453 - 0.546	0.454 - 0.559	0.455 - 0.566
mass (lb)	0.059 - 0.07	0.015 - 0.018	0.015 - 0.018	0.015 - 0.019
specific heat (Btu/lb °F)	0.158 - 0.16	0.158 - 0.16	0.158 - 0.16	0.158 - 0.16
Test No.	6 in. 27G #3S	12 in. 1G #25	12 in. 1G #32	12 in. 1G
Characteristic Temperature (CHTMP) (°F)	3.662 + 04	1.267 + 04	8.861 + 03	7.6 + 03
Characteristic Pressure (CHPRESS) (lb <sub>f</sub> /in. <sup>2</sup> )	5.195 + 02	3.606 + 02	4.094 + 02	4.053 + 02
LIQUID: density (lb/ft <sup>3</sup> )	94.139 - 93.009	94.32 - 93.53	93.42 - 92.39	94.31 - 93.34
mass (lb)	21.565 - 21.306	172.85 - 171.41	97.83 - 96.755	172.83 - 171.1
specific heat (Btu/lb °F)	0.226 - 0.229	0.225 - 0.227	0.228 - 0.231	0.225 - 0.228
thermal conductivity (Btu/hr ft °F)	0.039	0.040 - 0.039	0.039 - 0.038	0.04 - 0.039
viscosity (lb/ft hr)	1.177 - 1.088	1.193 - 1.127	1.19 - 1.044	1.191 - 1.113
kinematic viscosity (ft <sup>2</sup> /hr)	0.0125 - 0.01169	0.01264 - 0.01205	0.01197 - 0.0113	0.01263 - 0.0
Prandtl No.	6.746 - 6.4478	6.8 - 6.579	6.55 - 6.308	6.8 - 6.53
Modified Grashof No. = $f(q_H'', \tau = 1.)$ , $Gr_H^*$	1.431 + 16	1.37 + 15	1.26 + 14	8.422 + 14
Modified Grashof No. = $f(q_L'', \tau = 1.)$ , $Gr_L^*$	9.324 + 15	8.978 + 14	7.431 + 13	6.007 + 14
Interface No., I	0.00756	0.0218	0.03118	0.03633
ULLAGE: density (lb/ft <sup>3</sup> )	0.451 - 0.594	0.459 - 0.546	0.451 - 0.516	0.455 - 0.559
mass (lb)	0.015 - 0.019	0.12 - 0.143	0.472 - 0.541	0.119 - 0.146
specific heat (Btu/lb °F)	0.158 - 0.16	0.159 - 0.16	0.158 - 0.159	0.158 - 0.16

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Table A-1

- ULLAGE PROPERTIES (Page 1 of 2)

8G #1	6 in. 8G #14	6 in. 8G #10S	6 in. 8G #3	6 in. 8G #4	6 in. 8G #13	6 in. 27G #1S
03	1.140 + 03	8.867 + 03	1.267 + 04	7.598 + 03	1.14 + 03	2.838 + 04
02	4.058 + 02	2.948 + 02	3.609 + 02	4.058 + 02	4.058 + 02	4.028 + 02
- 93.529	94.335 - 93.562	94.394 - 93.775	94.364 - 93.618	94.364 - 93.491	93.449 - 93.66	94.174 - 93.241
- 21.425	21.61 - 21.433	12.356 - 12.275	21.616 - 21.445	21.616 - 21.416	21.407 - 21.455	12.327 - 12.205
0.227	0.225 - 0.227	0.225 - 0.227	0.225 - 0.227	0.225 - 0.228	0.228 - 0.227	0.226 - 0.228
0.039	0.04 - 0.039	0.04 - 0.039	0.04 - 0.039	0.04 - 0.039	0.039	0.039
- 1.127	1.194 - 1.13	1.199 - 1.147	1.196 - 1.134	1.196 - 1.124	1.121 - 1.137	1.18 - 1.105
96 - 0.012049	0.01265 - 0.01207	0.0127 - 0.012226	0.012678 - 0.012112	0.012678 - 0.012022	0.01199 - 0.01214	0.01253 - 0.01185
6.578	6.805 - 6.587	6.822 - 6.644	6.813 - 6.60145	6.813 - 6.568	6.557 - 6.6126	6.757 - 6.504
+ 14	1.228 + 14	1.202 + 14	1.354 + 15	8.262 + 14	1.247 + 14	1.394 + 15
14	6.999 + 13	7.193 + 13	8.385 + 14	5.319 + 14	8.211 + 13	9.531 + 14
	0.242	0.03106	0.0218	0.0363	0.242	0.00977
- 0.559	0.455 - 0.566	0.464 - 0.741	0.456 - 0.782	0.458 - 0.902	0.456 - 0.765	0.461 - 0.536
- 0.018	0.015 - 0.019	0.061 - 0.097	0.015 - 0.026	0.015 - 0.03	0.015 - 0.025	0.06 - 0.07
- 0.16	0.158 - 0.16	0.159 - 0.162	0.158 - 0.162	0.159 - 0.163	0.158 - 0.162	0.159 - 0.16
1G #32	12 in. 1G #22	12 in. 1G #15	12 in. 1G #35	12 in. 1G #17	12 in. 1G #28	18 in. 1G #D
+ 03	7.6 + 03	1.14 + 03	8.851 + 03	1.268 + 04	7.597 + 03	2.859 + 04
+ 02	4.053 + 02	4.013 + 02	2.835 + 02	3.606 + 02	4.053 + 02	4.069 + 02
- 92.39	94.31 - 93.34	94.293 - 93.416	94.34 - 93.7	94.29 - 93.449	94.306 - 93.299	94.326 - 93.55
- 96.755	172.83 - 171.06	172.8 - 171.19	98.79 - 98.122	172.795 - 171.254	172.825 - 170.979	333.377 - 330.633
- 0.231	0.225 - 0.228	0.225 - 0.228	0.225 - 0.227	0.225 - 0.228	0.225 - 0.228	0.225 - 0.227
- 0.038	0.04 - 0.039	0.039	0.04 - 0.039	0.039	0.039	0.040 - 0.039
- 1.044	1.191 - 1.113	1.19 - 1.118	1.194 - 1.14	1.19 - 1.121	1.191 - 1.109	1.193 - 1.129
7 - 0.0113	0.01263 - 0.01192	0.01262 - 0.01197	0.01265 - 0.01217	0.01262 - 0.01199	0.01263 - 0.01189	0.01265 - 0.01206
6.308	6.8 - 6.53	6.792 - 6.549	6.8 - 6.623	6.79 - 6.557	6.796 - 6.519	6.802 - 6.584
14	8.422 + 14	1.251 + 14	1.212 + 14	1.586 + 15	8.473 + 14	1.349 + 15
+ 13	6.007 + 14	8.186 + 13	7.733 + 13	9.673 + 14	6.305 + 13	7.335 + 14
8	0.03633	0.2423	0.03118	0.0218	0.03633	0.00966
- 0.516	0.455 - 0.559	0.458 - 0.549	0.453 - 0.827	0.480 - 0.828	0.458 - 1.037	0.445 - 0.513
- 0.541	0.119 - 0.146	0.12 - 0.144	0.474 - 0.866	0.126 - 0.217	0.120 - 0.272	1.572 - 1.814
- 0.159	0.158 - 0.16	0.159 - 0.16	0.158 - 0.163	0.159 - 0.163	0.159 - 0.164	0.158 - 0.159

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Table A  
FREON 113 PCA LIQUID - ULLAGE

Test No.	6 in. 8G #15S	6 in. 8G #12S	6 in. 8G #5	6 in. 8G #16S
Characteristic Temperature (CHTMP) (°F)	8.88 + 03	1.269 + 04	7.592 + 03	8.868 + 03
Characteristic Pressure (CHPRESS) (lb <sub>f</sub> /in. <sup>2</sup> )	4.212 + 02	3.699 + 02	3.968 + 02	2.948 + 02
LIQUID: density (lb/ft <sup>3</sup> )	94.314 - 93.48	94.282 - 93.556	94.411 - 93.456	94.392 - 93.749
mass (lb)	12.346 - 12.237	21.598 - 21.431	21.627 - 21.431	12.356 - 12.272
specific heat (Btu/lb °F)	0.225 - 0.228	0.225 - 0.227	0.225 - 0.227	0.225 - 0.227
thermal conductivity (Btu/hr ft °F)	0.04 - 0.039	0.039	0.04 - 0.039	0.04 - 0.039
viscosity (lb/ft hr)	1.192 - 1.123	1.189 - 1.129	1.201 - 1.129	1.199 - 1.144
kinematic viscosity (ft <sup>2</sup> /hr)	0.01264 - 0.01201	0.012613 - 0.012068	0.012716 - 0.012068	0.0127 - 0.01221
Prandtl No.	6.798 - 6.565	6.79 - 6.585	6.827 - 6.585	6.822 - 6.636
Modified Grashof No. = $f(q_H^u, \tau = 1.)$ , $Gr_H^*$	1.253 + 14	1.367 + 15	8.185 + 14	1.207 + 14
Modified Grashof No. = $f(q_L^u, \tau = 1.)$ , $Gr_L^*$	7.069 + 13	8.235 + 14	5.279 + 14	7.506 + 13
Interface No., 1	0.03106	0.0218	0.0363	0.03106
ULLAGE: density (lb/ft <sup>3</sup> )	0.46 - 0.547	0.458 - 0.564	0.451 - 0.568	0.456 - 0.745
mass (lb)	0.06 - 0.072	0.015 - 0.018	0.015 - 0.019	0.06 - 0.098
specific heat (Btu/lb °F)	0.159 - 0.16	0.159 - 0.16	0.158 - 0.16	0.158 - 0.162

Test No.	12 in. 1G #33	12 in. 1G #30	12 in. 1G #20	12 in. 1G #26
Characteristic Temperature (CHTMP) (°F)	8.859 + 03	1.267 + 04	7.599 + 03	1.14 + 03
Characteristic Pressure (CHPRESS) (lb <sub>f</sub> /in. <sup>2</sup> )	4.094 + 02	3.606 + 02	4.053 + 02	4.013 + 02
LIQUID: density (lb/ft <sup>3</sup> )	94.282 - 93.426	94.309 - 93.517	94.29 - 93.364	94.295 - 93.382
mass (lb)	98.732 - 97.835	172.83 - 171.378	172.794 - 171.099	172.805 - 171.132
specific heat (Btu/lb °F)	0.225 - 0.228	0.225 - 0.227	0.225 - 0.228	0.225 - 0.228
thermal conductivity (Btu/hr ft °F)	0.039	0.040 - 0.039	0.039	0.039
viscosity (lb/ft hr)	1.189 - 1.119	1.191 - 1.126	1.19 - 1.114	1.19 - 1.115
kinematic viscosity (ft <sup>2</sup> /hr)	0.01261 - 0.01254	0.01263 - 0.01204	0.01262 - 0.01193	0.01262 - 0.01194
Prandtl No.	6.789 - 6.551	6.797 - 6.575	6.791 - 6.535	6.793 - 6.54
Modified Grashof No. = $f(q_H^u, \tau = 1.)$ , $Gr_H^*$	1.259 + 14	1.373 + 15	8.401 + 14	1.257 + 14
Modified Grashof No. = $f(q_L^u, \tau = 1.)$ , $Gr_L^*$	7.511 + 13	9.024 + 14	5.744 + 14	8.563 + 13
Interface No., 1	0.03118	0.0218	0.03633	0.2423
ULLAGE: density (lb/ft <sup>3</sup> )	0.46 - 0.520	0.46 - 0.547	0.454 - 0.554	0.454 - 0.545
mass (lb)	0.481 - 0.544	0.121 - 0.143	0.119 - 0.145	0.119 - 0.143
specific heat (Btu/lb °F)	0.159	0.159 - 0.160	0.158 - 0.16	0.158 - 0.16

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Table A-1

LIQUID - ULLAGE PROPERTIES (Page 2 of 2)

#5	6 in. 8G #16S	6 in. 8G #11S	6 in. 8G #6	6 in. 8G #8S	6 in. 1G #1	6 in. 1G #2	
	8.868 + 03	1.2654 + 04	7.603 + 03	7.581 + 03	7.596 + 03	7.605 + 03	
	2.948 + 02	3.609 + 02	4.112 + 02	3.968 + 02	4.004 + 02	4.004 + 02	
556	94.392 - 93.749	94.457 - 93.692	94.327 - 93.394	94.493 - 93.651	94.38 - 93.544	94.315 - 93.491	
431	12.356 - 12.272	21.638 - 21.463	21.608 - 21.394	21.646 - 21.453	21.52 - 21.428	21.6 - 21.416	
27	0.225 - 0.227	0.225 - 0.227	0.225 - 0.228	0.225 - 0.227	0.225 - 0.227	0.225 - 0.228	
9	0.04 - 0.039	0.04 - 0.039	0.04 - 0.039	0.04 - 0.039	0.04 - 0.039	0.04 - 0.039	
29	1.199 - 1.144	1.205 - 1.14	1.193 - 1.116	1.208 - 1.137	1.198 - 1.128	1.192 - 1.124	
0.012068	0.0127 - 0.01221	0.01275 - 0.012166	0.01265 - 0.01195	0.01278 - 0.01214	0.01269 - 0.01206	0.01264 - 0.01202	
85	6.822 - 6.636	6.84 - 6.621	6.802 - 6.543	6.852 - 6.61	6.818 - 6.582	6.799 - 6.568	
	1.207 + 14	1.339 + 15	8.373 + 14	8.073 + 14	1.025 + 14	1.033 + 14	
	7.506 + 13	8.493 + 14	5.687 + 14	5.13 + 14	6.415 + 13	6.368 + 13	
	0.03106	0.0218	0.0363	0.0363	0.0363	0.0363	
68	0.456 - 0.745	0.456 - 0.767	0.458 - 0.964	0.453 - 0.554	0.449 - 0.54	0.455 - 0.561	
19	0.06 - 0.098	0.015 - 0.025	0.015 - 0.032	0.015 - 0.018	0.015 - 0.018	0.015 - 0.018	
6	0.158 - 0.162	0.158 - 0.162	0.159 - 0.164	0.158 - 0.16	0.158 - 0.16	0.158 - 0.16	
#20	12 in. 1G #26	12 in. 1G #34	12 in. 1G #31	12 in. 1G #23	12 in. 1G #27	18 in. 1G #BS	18 in. 1G #IS
	1.14 + 03	8.858 + 03	1.267 + 04	7.594 + 03	1.14 + 03	2.863 + 04	3.668 + 04
	4.013 + 02	2.835 + 02	3.606 + 02	4.053 + 02	4.013 + 02	4.069 + 02	5.214 + 02
364	94.295 - 93.382	94.287 - 93.613	93.462 - 92.58	94.333 - 93.215	94.276 - 93.236	94.253 - 93.493	94.261 - 93.218
71.099	172.805 - 171.132	98.738 - 98.032	171.278 - 169.662	172.874 - 170.826	172.769 - 170.863	333.117 - 330.432	583.006 - 576.556
28	0.225 - 0.228	0.225 - 0.227	0.228 - 0.23	0.225 - 0.228	0.225 - 0.228	0.225 - 0.228	0.225 - 0.228
	0.039	0.039	0.039 - 0.038	0.04 - 0.039	0.039	0.039	0.039
4	1.19 - 1.115	1.19 - 1.134	1.122 - 1.057	1.194 - 1.103	1.189 - 1.104	1.187 - 1.124	1.187 - 1.103
0.01193	0.01262 - 0.01194	0.01262 - 0.012109	0.012 - 0.01142	0.01265 - 0.01183	0.01261 - 0.01184	0.01259 - 0.01202	0.0126 - 0.01183
35	6.793 - 6.54	6.79 - 6.6	6.561 - 6.349	6.804 - 6.498	6.787 - 6.503	6.78 - 6.569	6.782 - 6.498
	1.257 + 14	1.227 + 14	1.383 + 15	8.565 + 14	1.282 + 14	1.36 + 15	1.395 + 16
	8.563 + 13	8.319 + 13	9.686 + 14	7.075 + 13	9.954 + 13	7.238 + 14	8.357 + 15
	0.2423	0.03118	0.0218	0.03633	0.2423	0.00966	0.00754
54	0.454 - 0.545	0.463 - 0.844	0.462 - 0.9	0.458 - 1.007	0.463 - 0.812	0.46 - 0.531	0.465 - 0.607
45	0.119 - 0.143	0.485 - 0.884	0.121 - 0.236	0.12 - 0.264	0.121 - 0.213	1.624 - 1.275	0.411 - 0.536
5	0.158 - 0.16	0.159 - 0.163	0.159 - 0.163	0.159 - 0.164	0.159 - 0.163	0.159 - 0.16	0.159 - 0.16

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## Appendix B

### TEST CONDITIONS AND TABULATED SENSIBLE HEAT DATA

This appendix contains the input heater heat flux, liquid (Freon 113 PCA) level, and stratification test time for each test investigated. Included are the tabulated sensible heat gains by the test liquid, ullage, and the test tank structures, the tank wall, the foam insulation, and the silicone rubber heaters. This information is shown in Table E-1.

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Table B-1

TEST CONDITIONS - SUPPLIED  
SENSIBLE HEAT GAINS

Test No.	6 in. 8G No. 9S	6 in. 8G No. 2	6 in. 8G No. 1	6 in. 8G No. 1
Liquid Level (percent)	50.0	87.5	87.5	87.5
Heating Condition	Liquid	Liquid	Liquid	Liquid
Liquid Heater Electrical Source $q''_H$ (Btu/hr ft <sup>2</sup> )	701.569	1001.99	600.85	600.85
Ullage Heater Electrical Source $q''_H$ (Btu/hr ft <sup>2</sup> )	0.0	0.0	0.0	0.0
Stratification Test Time (minute)	3.33	2.0	3.666	3.666
Liquid Total Energy Supplied (Btu)	45.913	65.58	71.966	71.966
Ullage Total Energy Supplied (Btu)	0.0	0.0	0.0	0.0
Summation - Total Energy Supplied (Btu)	45.913	65.58	71.966	71.966
Liquid - Measured Heat Flux $q''_l$ (Btu/hr ft <sup>2</sup> )	368.248	582.284	389.008	389.008
Ullage - Measured Heat Flux $q''_u$ (Btu/hr ft <sup>2</sup> )	1.744	2.566	1.604	1.604
Tank - Stainless Wall - Measured Sensible Heat (Btu)	6.089	7.867	7.244	7.244
Silicone Heaters - Measured Sensible Heat (Btu)	4.384	5.89	5.42	5.42
Foam Insulation - Measured Sensible Heat (Btu)	8.675	9.095	9.233	9.233
Freon 113 (PCA) - Measured Sensible Heat (Btu)	24.102	38.11	46.669	46.669
Ullage - Measured Sensible Heat (Btu)	0.114	0.034	0.038	0.038
Summation - Measured Absorbed Sensible Heat (Btu)	43.364	60.996	68.604	68.604
Percent - Measured Absorbed Heat/Total Energy Supplied	94.44	93.01	95.32	95.32

Test No.	12 in. 1G No. 25	12 in. 1G No. 32	12 in. 1G No. 22	12 in. 1G No. 22
Liquid Level (percent)	87.5	50.0	87.5	87.5
Heating Condition	Liquid	Liquid	Liquid	Liquid
Liquid Heater Electrical Source $q''_H$ (Btu/hr ft <sup>2</sup> )	500.56	349.77	300.077	300.077
Ullage Heater Electrical Source $q''_H$ (Btu/hr ft <sup>2</sup> )	0.0	0.0	0.0	0.0
Stratification Test Time (minute)	8.0	13.0	15.0	15.0
Liquid Total Energy Supplied (Btu)	524.188	357.123	589.2	589.2
Ullage Total Energy Supplied (Btu)	0.0	0.0	0.0	0.0
Summation - Total Energy Supplied (Btu)	524.188	357.123	589.2	589.2
Liquid - Measured Heat Flux $q''_l$ (Btu/hr ft <sup>2</sup> )	328.14	206.34	214.021	214.021
Ullage - Measured Heat Flux $q''_u$ (Btu/hr ft <sup>2</sup> )	1.194	0.723	0.767	0.767
Tank - Stainless Wall - Measured Sensible Heat (Btu)	64.858	47.752	61.65	61.65
Silicone Heaters - Measured Sensible Heat (Btu)	21.58	16.912	22.237	22.237
Foam Insulation - Measured Sensible Heat (Btu)	72.78	67.448	72.869	72.869
Freon 113 PCA - Measured Sensible Heat (Btu)	343.629	210.677	420.229	420.229
Ullage - Measured Sensible Heat (Btu)	0.25	0.738	0.301	0.301
Summation - Measured Absorbed Sensible Heat (Btu)	505.097	342.789	577.286	577.286
Percent - Measured Absorbed Heat/Total Energy Supplied	96.35	95.98	97.97	97.97

FOLDOUT FRAME

Table B-1

CTIONS - SUPPLIED HEAT FLUXES -  
BLE HEAT GAINS (Page 1 of 2)

6 in. 8G No. 1	6 in. 8G No. 14	6 in. 8G No. 10S	6 in. 8G No. 3	6 in. 8G No. 4	6 in. 8G No. 13	6 in. 27G No. 1S	6 in. 27G No. 3S
87.5 Liquid	87.5 Liquid	50.0 Liquid and Ullage	87.5 Liquid and Ullage	97.5 Liquid and Ullage	87.5 Liquid and Ullage	50.0 Liquid	87.5 Liquid
600.85	90.127	701.569	1001.99	600.85	90.127	2236.686	2884.422
0.0	0.0	701.569	1001.99	600.85	90.127	0.0	0.0
3.666	25.0	2.333	2.0	3.75	25.0	1.0	1.0
71.966	73.735	32.142	65.58	73.735	73.735	43.917	94.392
0.0	0.0	32.142	13.116	14.747	14.747	0.0	0.0
71.966	73.735	64.284	78.696	88.482	88.482	43.917	94.392
389.008	51.382	419.734	620.367	386.81	59.366	1529.462	1880.114
1.604	0.249	14.206	10.772	3.338	0.809	5.611	8.264
7.244	5.421	18.8	15.867	13.067	8.756	5.91	10.355
5.42	3.892	13.396	9.65	9.049	5.612	4.146	7.8
9.233	9.116	12.54	11.16	11.099	10.219	8.949	10.438
46.669	42.037	19.23	40.603	47.469	48.569	29.031	61.527
0.038	0.041	0.465	0.141	0.206	0.132	0.107	0.054
68.604	60.507	64.431	77.421	89.89	73.288	48.143	90.174
95.32	82.06	100.22	98.37	93.68	82.82	109.62	95.53
12 in. 1G No. 22	12 in. 1G No. 15	12 in. 1G No. 35	12 in. 1G No. 17	12 in. 1G No. 28	18 in. 1G No. D		
87.5 Liquid	87.5 Liquid	50.0 Liquid and Ullage	87.5 Liquid and Ullage	87.5 Liquid and Ullage	50.0 Liquid		
300.077	45.012	349.77	500.56	300.077	753.15		
0.0	0.0	350.35	500.56	300.124	0.0		
15.0	99.0	9.0	8.0	15.0	9.0		
589.2	583.31	247.239	524.188	589.2	1197.835		
0.0	0.0	247.648	104.84	117.976	0.0		
589.2	583.31	494.887	629.028	707.176	1197.835		
214.021	29.444	223.179	349.47	223.311	409.627		
0.767	0.101	7.55	5.763	5.844	1.639		
61.65	39.912	168.205	109.404	125.084	201.998		
22.237	14.22	60.041	34.077	37.234	49.189		
72.869	68.84	105.571	86.48	89.537	238.016		
420.229	381.562	157.756	365.964	438.47	651.483		
0.301	0.262	5.336	1.207	2.295	2.607		
577.286	504.796	496.909	597.132	692.62	1143.293		
97.97	86.53	100.4	94.92	97.94	95.44		

FOLDOUT FRAME

2

Table B-1  
TEST CONDITIONS - SUPPLY  
SENSIBLE HEAT GAIN

Test No.	6 in. 8G No. 15S	6 in. 8G No. 12S	6 in. 8G No. 5
Liquid Level (percent)	50.0	87.5	87.5
Heating Condition	Liquid	Liquid	Liquid
Liquid Heater Electrical Source $q''_H$ (Btu/hr ft <sup>2</sup> )	701.57	1001.99	600.85
Ullage Heater Electrical Source $q''_H$ (Btu/hr ft <sup>2</sup> )	0.0	0.0	0.0
Stratification Test Time (minute)	3.333	2.0	3.667
Liquid Total Energy Supplied (Btu)	45.92	65.58	72.095
Ullage Total Energy Supplied (Btu)	0.0	0.0	0.0
Summation - Total Energy Supplied (Btu)	45.917	65.58	72.095
Liquid - Measured Heat Flux $q''_l$ (Btu/hr ft <sup>2</sup> )	395.894	603.703	387.535
Ullage - Measured Heat Flux $q''_u$ (Btu/hr ft <sup>2</sup> )	1.903	2.952	1.8
Tank - Stainless Wall - Measured Sensible Heat (Btu)	6.222	8.044	7.467
Silicone Heaters - Measured Sensible Heat (Btu)	4.464	5.977	5.523
Foam Insulation - Measured Sensible Heat (Btu)	8.827	9.267	9.263
Freon 113 PCA - Measured Sensible Heat (Btu)	25.911	39.512	46.5
Ullage - Measured Sensible Heat (Btu)	0.125	0.039	0.043
Summation - Measured Absorbed Sensible Heat (Btu)	45.549	62.839	68.796
Percent - Measured Absorbed Heat/Total Energy Supplied	99.19	95.82	95.42

Test No.	12 in. 1G No. 33	12 in. 1G No. 30	12 in. 1G No. 20
Liquid Level (percent)	50.0	87.5	87.5
Heating Condition	Liquid	Liquid	Liquid
Liquid Heater Electrical Source $q''_H$ (Btu/hr ft <sup>2</sup> )	349.77	500.56	300.077
Ullage Heater Electrical Source $q''_H$ (Btu/hr ft <sup>2</sup> )	0.0	0.0	0.0
Stratification Test Time (minute)	13.0	8.0	15.0
Liquid Total Energy Supplied (Btu)	357.123	524.188	589.2
Ullage Total Energy Supplied (Btu)	0.0	0.0	0.0
Summation - Total Energy Supplied (Btu)	357.123	524.188	589.2
Liquid - Measured Heat Flux $q''_l$ (Btu/hr ft <sup>2</sup> )	208.707	362.662	205.171
Ullage - Measured Heat Flux $q''_u$ (Btu/hr ft <sup>2</sup> )	0.657	1.192	0.74
Tank - Stainless Wall - Measured Sensible Heat (Btu)	41.338	64.858	59.513
Silicone Heaters - Measured Sensible Heat (Btu)	14.729	23.568	21.484
Foam Insulation - Measured Sensible Heat (Btu)	66.745	73.774	77.077
Freon 113 PCA - Measured Sensible Heat (Btu)	213.093	314.63	402.851
Ullage - Measured Sensible Heat (Btu)	0.671	0.250	0.291
Summation - Measured Absorbed Sensible Heat (Btu)	336.576	477.08	561.216
Percent - Measured Absorbed Heat/Total Energy Supplied	94.24	91.01	95.25

FOLDOUT FRAME

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Table E-1

ITIONS - SUPPLIED HEAT FLUXES -  
BLE HEAT GAINS (Page 2 of 2)

	6 in. 8G No. 5	6 in. 8G No. 16S	6 in. 8G No. 11S	6 in. 8G No. 6	6 in. 8G No. 8S	6 in. 1G No. 1	6 in. 1G No. 2	
	87.5 Liquid	50.0 Liquid and Ullage	87.5 Liquid and Ullage	87.5 Liquid and Ullage	87.5 Liquid and Ullage	87.5 Liquid and Ullage	87.5 Liquid and Ullage	
	600.85	701.569	1001.99	600.85	600.85	600.85	600.85	
	0.0	701.569	1001.99	600.85	0.0	0.0	0.0	
	3.667	2.333	2.0	3.8	3.667	3.7	3.7	
	72.095	32.142	65.58	74.718	72.095	72.752	72.752	
	0.0	32.142	13.116	14.944	0.0	0.0	0.0	
	72.095	64.284	78.696	89.662	72.095	72.752	72.752	
	387.535	436.428	635.42	408.07	381.824	375.963	370.305	
	1.8	10.662	10.178	9.723	1.517	1.356	1.594	
	7.467	19.823	15.645	15.912	6.978	8.4	8.488	
	5.523	14.182	9.535	9.607	5.167	6.246	6.233	
	9.263	12.896	11.26	11.375	9.031	9.633	9.758	
	46.5	19.995	41.588	50.745	45.815	45.522	44.837	
	0.043	0.488	0.133	0.242	0.036	0.033	0.039	
	68.796	67.384	78.161	87.881	67.027	69.854	69.355	
	95.42	104.82	99.32	98.01	92.97	96.01	95.33	
	12 in. 1G No. 20	12 in. 1G No. 26	12 in. 1G No. 34	12 in. 1G No. 31	12 in. 1G No. 23	12 in. 1G No. 27	18 in. 1G No. BS	18 in. 1G No. IS
	87.5 Liquid	87.5 Liquid	50.0 Liquid and Ullage	87.5 Liquid and Ullage	87.5 Liquid and Ullage	87.5 Liquid and Ullage	50.0 Liquid	87.5 Liquid
	300.077	45.012	349.772	500.563	300.077	45.0116	753.151	965.0435
	0.0	0.0	350.33	500.563	300.424	45.0637	0.0	0.0
	15.0	99.0	9.0	8.0	15.0	99.0	9.0	9.0
	589.2	583.308	247.239	524.188	589.2	583.308	1197.835	2558.06
	0.0	0.0	247.239	104.838	117.976	116.797	0.0	0.0
	589.2	583.308	494.887	529.026	707.176	700.105	1197.835	2558.06
	205.171	30.664	237.126	350.637	247.854	34.946	400.823	578.124
	0.74	0.102	7.69	7.732	5.459	0.472	1.723	2.73
	59.513	40.625	162.86	128.648	126.866	73.411	206.696	302.998
	21.484	14.514	57.597	38.45	37.778	22.89	49.245	74.144
	77.077	75.495	103.787	90.176	90.516	77.084	243.66	276.177
	402.851	397.382	167.614	367.186	486.661	452.867	637.481	1532.445
	0.291	0.264	5.436	1.619	2.144	1.223	2.740	1.447
	561.216	528.28	497.294	626.079	743.965	627.475	1139.822	2187.211
	95.25	90.56	100.48	99.53	105.2	89.62	95.15	85.5

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